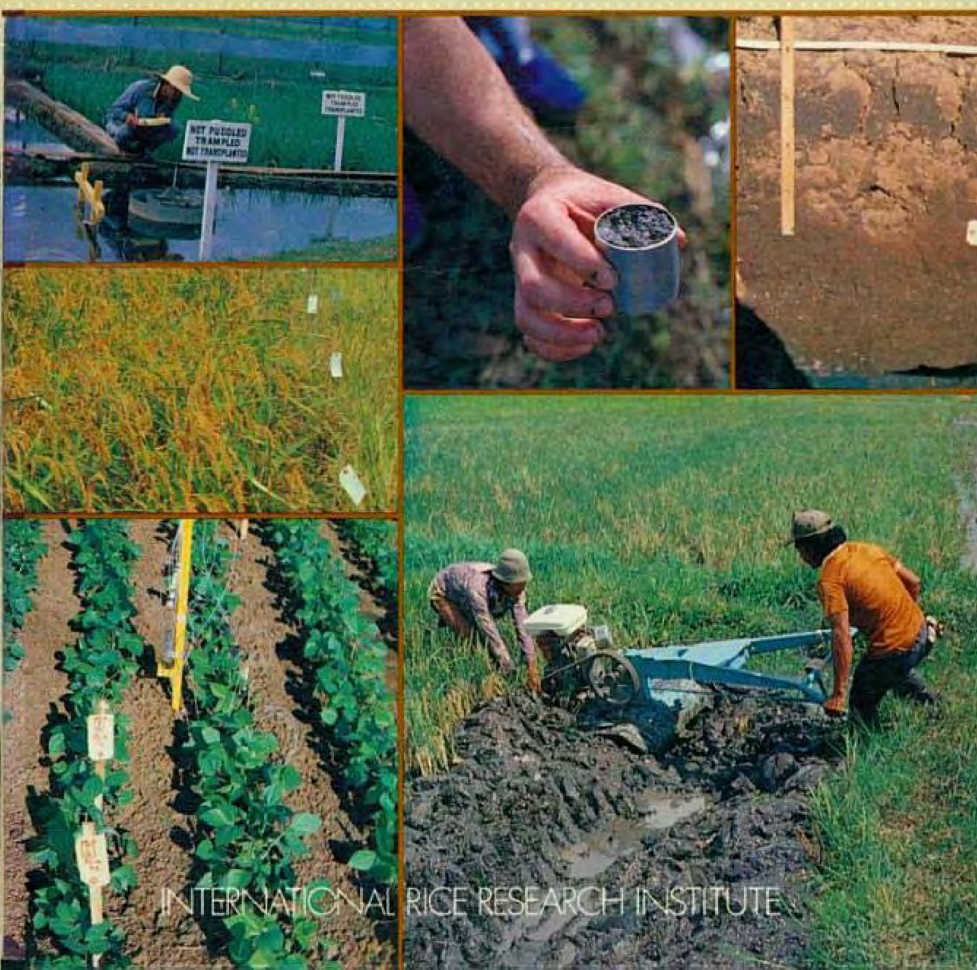
SOIL PHYSICS AND RICE



INTERNATIONAL RICE RESEARCH INSTITUTE

SOIL PHYSICS AND RICE

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The International Rice Research Institute (IRRI) was established in 1960 by the Ford and Rockfeller Foundations with the help and approval of the Government of the Philippines. Today IRRI is one of the 13 nonprofit international research and training centers supported by the Consultative Group for International Agricultural Research (CGIAR). The CGIAR is sponsored by the Food and Agriculture Organization (FAO) of the United Nations, the International Bank for Reconstructionn and Development (World Bank), and the United Nations development Programme (UNDP). The CGIAR consists of 50 donor countries, international and regional organizations, and private foundations.

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FOREWORD

Asian lowlands have for many centuries produced enough rice for very large populations. Recently, food production has increased slightly more rapidly than population growth. Increases were through combinations of expanded irrigation, high yielding varieties, chemical fertilizers, and cropping intensification. However, they will not necessarily continue. The recent increases were primarily from lands with fertile soil and favorable climate. There are few opportunities for developing new land. Rice and other crops must now be grown where water is not well controlled, soils are less fertile, or there are physical constraints such as compacted soil layers. To increase production in these areas will be difficult.

In Africa and parts of South America, population growth exceeds increases in food production. Governments in those continents are looking increasingly to rice and rice-based cropping systems for the extra food that they need now and shall need more pressingly in the future. As in Asia, there are soil physical constraints to rapid, large-scale expansion of production from rice-based systems.

Thus, with a world demand for rice that is expected to grow by an annual 3% for the next 15 yr, it is essential that improved soil and water management methods be developed and adopted for ricelands, both to increase food production and to avoid soil erosion and degradation.

These issues and problems were addressed in the Workshop on Physical Aspects of Soil Management in Rice-based Cropping Systems at IRRI 10-14Dec 1984. It was attended by 55 participants from 21 countries and by several IRRI staff members.

IRRI wishes to thank for their support the Agency for Cooperation in Development of the Belgian Government, which provided a large part of the needed funds, the United Nations Development Programme, the United Nations Environment

Programme, the International Board for Soil Research and Management, and the national governments that sponsored individual participants.

T. Woodhead was workshop convenor and scientific editor. He was assisted by a committee comprising S.I. Bhuiyan, C.W. Bockhop, G. Boje-Klein, S.K. De Datta, D.P. Garrity, D.J. Greenland, R.A. Morris, H. Murray-Rust, H.U. Neue, L.R. Oldeman, J.C. O'Toole, F.N. Ponnamperuma, V.M. Segovia, and E.A. Tout. The proceedings were edited by E.A. Tout assisted by G.S. Argosino. The proceedings include 26 papers, 19 poster abstracts, and recommendations for future research, training, and coordination of programs.

Participants concluded that there is significant potential to develop practical technologies that will increase food production from lowland rice-based cropping systems. Essential to these increases will be applied research on those physical aspects of soil management that now limit food production.

M.S. Swaminathan
Director General

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PHYSICAL ASPECTS OF SOIL MANAGEMENT FOR RICE-BASED CROPPING SYSTEMS

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ABSTRACT

Food production from the tropical wetlands of Asia and the world must be increased. There are physical problems of wetland soil and water management that restrict rice production. Drainage and soil strength determine appropriate soil management, and structural alterations caused by puddling and redrying affect rice and upland crops grown after rice. The hydrology of ricelands should be studied and related to soil characteristics. More trained physicists are needed to tackle these tasks, and ways must be found to facilitate greater collaboration among the few physicists and agronomists conducting research on physical aspects of wetland soil management.

PHYSICAL ASPECTS OF SOIL MANAGEMENT FOR RICE-BASED CROPPING SYSTEMS

For centuries, rice has been grown on Asian wetlands where soils are flooded, usually to depths of 5-10 cm of water, throughout the growing season. In the relatively fertile alluvial soils of the river floodplains and estuaries of Asia, and in the volcanic soils of Indonesia and the Philippines, this management system is very productive, and has supported large populations for many years. Rice also is grown where water is less well controlled. About half the rice in the tropics endures drought, short periods of total submergence, or rice grows in water that can be several metres deep.

Rice demand has grown at an annual rate of approximately 3% for the last 20 yr, and is expected to continue at that rate until the end of the century. Better water management, improved varieties, fertilizers, and organic manures have helped production keep pace with demand. In some environments, production has been increased by growing two or three rice crops per year, or an upland crop before or after one or two rice crops.

Almost all rice is consumed near where it is grown. World trade in rice is only 12 million t annually, and production is almost 450 million t. In China, which produces one-third of the world's rice, national average crop yield exceeds 4 t/ha, and 2 annual crops are often harvested. Serious concern exists about the ability of the soils of China to support more intense cropping, and cropping intensity has been reduced in several areas. In parts of Bangladesh and eastern India, the problem is different. Rice in these stagnant water areas still yields less than 1 t/ha, despite many efforts to raise yields.

Only a part of the irrigated rice areas can rely on year-round water from storage systems. Most rice is grown in areas that receive monsoonal rainfall supplemented by water diverted from seasonal streams and rivers. In dry season, when irrigation water is unavailable, the land often lies idle. If a dryland crop is sown, seed establishment in the cloddy soil left after growing rice is poor and yields are low. Nevertheless, many of these soils are deep, loamy clays that contain enough water at the end of wet season to grow a short-duration crop of legume, sorghum, wheat, or maize, but crop establishment is difficult unless the soils can be tilled to a favorable physical condition.

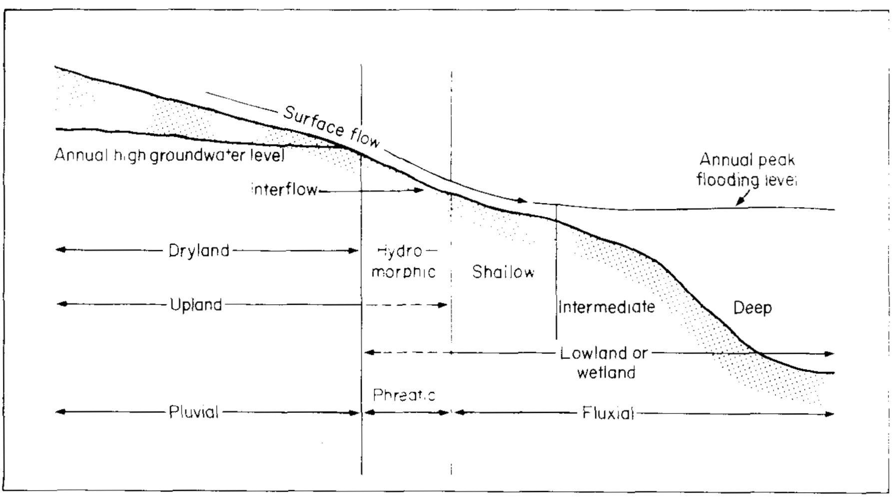
More food from Asian ricelands is vitally needed, but many soil management problems must be solved if the necessary production is to be obtained and sustained. Management problems include those related to physical properties such as permeability and aeration, soil strength, water retention, and structural condition for a dryland crop to be established following rice.

LAND WHERE RICE IS GROWN

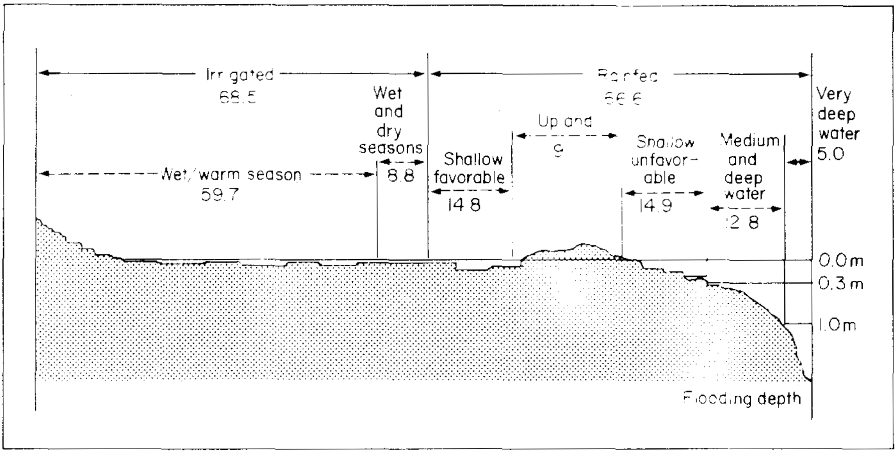
Most illustrations of rice cultivation in Asia show terraced fields with standing water and transplanted rice. Soil-physical properties largely determine the energy necessary for and success of tillage operations. Surprisingly little attention has been paid to the physical properties of rice soils. Research also has neglected the hydrology of land systems where rice is grown.

Moormann and van Breemen (13) summarized much of the existing knowledge of the relationship between landform, water, and soils used for rice production. Their work provides valuable background for studying land use and management for rice-based cropping systems.

They divide ricelands into pluvial, phreatic, and fluxial (Fig. 1). Most rice is grown on phreatic lands in monsoon areas where the water table is close to or above the soil surface throughout wet season, and where bunding retains surface water. There are 85 million ha of phreatic riceland, about 35 million ha of fluxial land, and about 20 million ha of pluvial land used for rice-based cropping systems (Fig. 2).



1. Terminology to describe riceland by topography and water supply (5).



2. World riceland by water regime (million hectares). The horizontal extent of each class is approximately proportional to the area (10).

On most pluvial land, rice is grown as a dryland crop, in much the same way as wheat or barley. Some originally pluvial lands in monsoon areas have been terraced and irrigated for rice production, creating the anthraquic ricelands with perched water tables described by Moormann and van Breemen (13). Soils of anthraquic ricelands resemble the European pseudogleys that are dominant in many phreatic areas.

In contrast, fluxial soils may be true gleys that are more or less permanently reduced throughout the profile. Where fluxial ricelands are difficult to drain, and subject to flash or extended flooding for much of the year, they can be used for specially adapted rice varieties, although yields often are low. Sometimes a dryland crop is grown after rice when floodwaters recede.

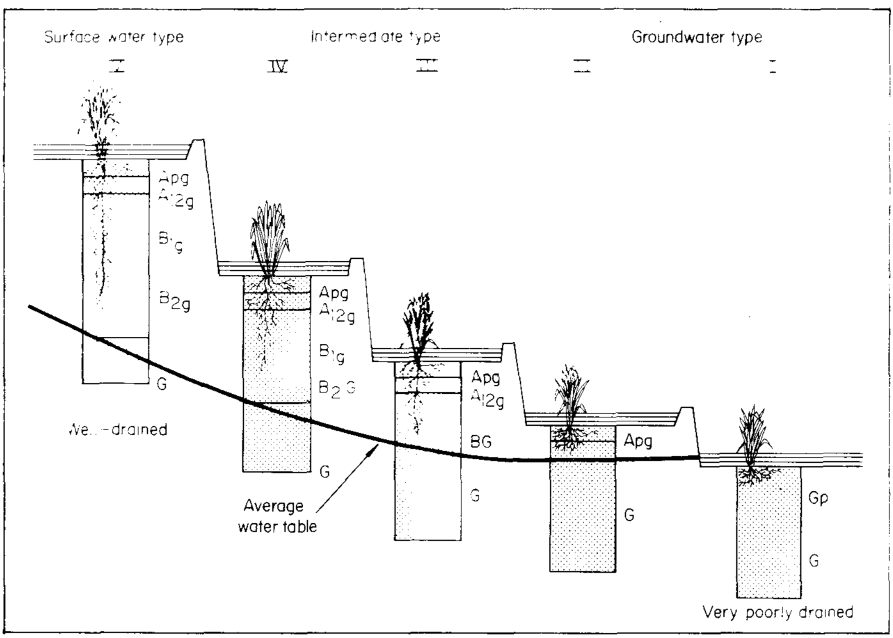
The typical sequence of soil profiles at different toposequence positions on phreatic and fluxial ricelands was described by Kanno (11) and others (Fig. 3). Most phreatic rice soils are medium- to heavy-textured and occupy low landscape positions. They generally are poorly drained, and the water table is at or near the surface for much of the rice season. Where soils at higher elevations are terraced for rice production, they must be well-puddled to impede percolation and allow easy levelling. Correspondingly, the bunds that hold water in the rice field must seal easily to minimize water losses by seepage. This problem is similar to that of sealing earthen dams (2). Thus, the physical properties of soils that determine water retention characteristics and ease of puddling are important.

In fluxial lands, seepage and percolation are seldom problems, but rice often yields poorly because of other adverse soil physical properties or because the crop is submerged. Thus in fields that may be relatively dry when rice is planted, it is important that the soil retains ample water and has a structure that encourages root proliferation.

DRAINAGE AND AERATION

Although rice grows well in flooded soils, proper drainage is very important. Farms on fluxial lands and at the tail end of irrigation systems suffer frequent flooding because of inadequate surface drainage. Although some rices can tolerate submergence for 10 d, most die after 1 or 2 d. Thus if water depth exceeds 30–35 cm, even for a short time, yields may be very low or nil. A few rices can elongate up to 10 cm/d to keep above rising floodwater, but they are neither high yielding nor of the semidwarf stature preferred by most farmers.

Irrigation raises the water table and reduces internal drainage at the tail end of the system, often changing pseudogleys into gleys. Swamp lands are used extensively for rice, but yields usually are low or very low.



3. Catenary sequence of five fundamental families of mineral rice soils (13, modified from 11).

The Chinese categorize rice soils as permeable, side bleaching, stagnating, waterlogged, or percolating (16). The soils are distinguished by the intensity and position of the gley horizon (Fig. 3). They also distinguish between high and low yielding rice soils: stagnating and waterlogged soils are low yielding.

According to Chen Jian-fongand Li Shi-ye (l), "farmers frequently take the proper percolation rate of the surface water over ricefields as an important criterion in evaluating the fertility of rice soils." Percolation rates for fertile rice soils are considered to be 9-15mm/d for Jiangsu Province (17) and Shanghai (6) and 7-20mm/d on the Zhujiang River Delta (6, 7). These soils produce 15-20 t rice/ha in 2 or 3 crops. Maintaining this cropping intensity for several years is likely to increase gleying and reduce yields unless the soil dries between rice crops (12).

There is little reported evidence that 10-20mm percolation/d is needed for high rice yields in the tropics. At IRRI, 3 crops of rice have been grown in each of 22 consecutive yr where percolation rate is less than 1 mm/d.

4. Yields of the best rice variety in dry season (DS). and early and late wet season (WS) in an IRRI continuous cropping experiment (8), 1968-82.

Although yields have slowly declined (Fig. 4), annual yield still exceeds 14 t/ha. Much more information is needed to relate yield, drainage regime, and other soil characteristics.

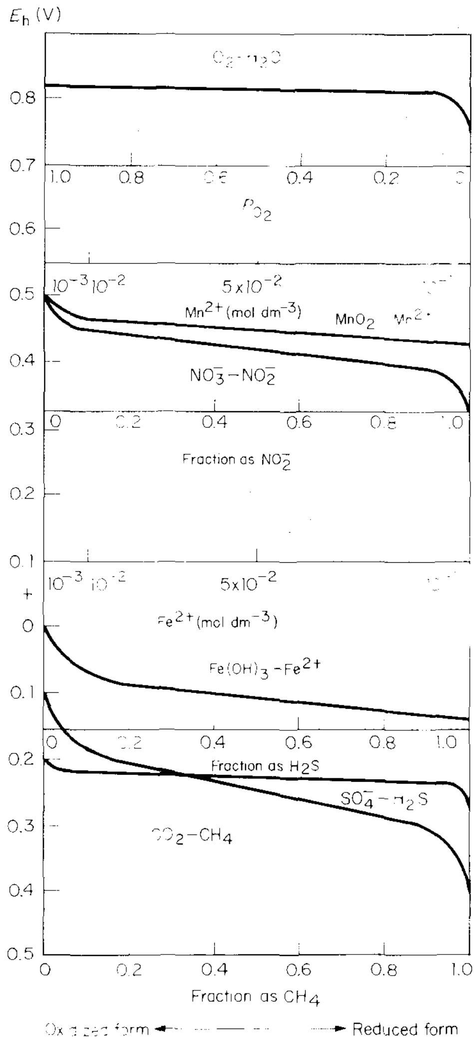
Oxygen-saturated surface water, which enters the soil through vertical percolation, prevents low reduction potential and consequent soil toxicities. When toxicities occur, they are most commonly caused by high levels of ferrous ions and very high levels of manganous ions in the soil solution, by certain organic acids, and occasionally by sulfide.

Figure 5 shows the redox potentials at which iron and manganese are reduced. Sulfide only forms if redox potential falls below -200mV, and then it often will promptly precipitate as ferrous sulfide. If some manganese dioxide is present, then close to the oxide and possibly elsewhere the redox potential remains above +400 mV so that the soil is buffered against serious reduction. Reduction processes are caused by microbial action, and depend on the presence of suitable organic substrates. Most commonly, the substrates come from residues of present or previous crops. As Ponnamperuma (14) showed, the rate of decrease of redox potential differs considerably between soils, and is affected by pH, temperature, available organic material, and other factors.

Oxygen also enters the soil through the aerenchyma of rice and other plant roots. However, this oxygen is largely used for root respiration and affects only the soil in the immediate vicinity of the roots. Thus, deposits of ferric hydroxide are commonly observed on rice root surfaces in strongly reduced soils. If this channeling of oxygen does not occur, the plant probably will suffer from Fe toxicity.

The drainage of waterlogged soils may be improved artificially, but usually at considerable cost, particularly if the soil is only slowly permeable. If the natural water table remains below about 50 cm, and surface water is introduced, infiltration depends on inherent soil profile characteristics. Most lowland rice soils are fine- to medium-textured, and therefore wet cultivation induces a very open structure in the plow layer (Fig. 6). However, wet cultivation also induces clay translocation and may form a denser layer. Percolation rate is determined either by this layer or the less permeable Bt horizon below it.

Pans are an almost universal feature of lowland rice soils. The extent to which they and the Bt horizon restrict percolation probably depends as much on annual soil drying as on soil texture. Drying causes soil to shrink, and fissures and transmission pores to develop. This drying usually is more intense when a crop is grown -- as with a dryland crop grown on residual water after monsoon rice. Such drying

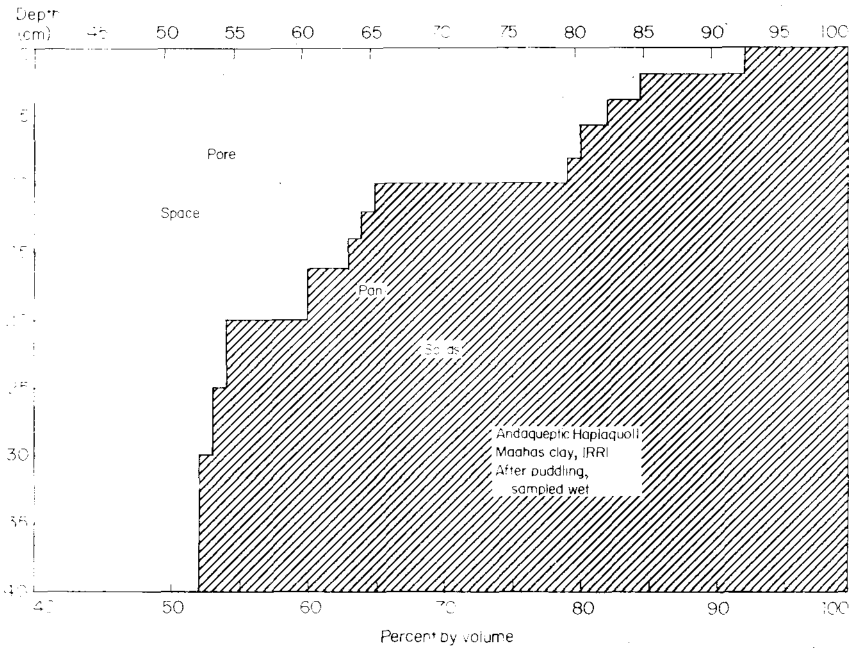


5. Relations between redox potential and the composition of important redox couples in soils (15).

may affect the soil horizons beneath the cultivation pan if the water table recedes below 1.5 m depth.

Soils swell when they are reflooded. The fissures and transmission pores then tend to close, but they normally persist sufficiently long to allow some percolation. Where the fissures develop along root channels, their walls may be stabilized by root exudates and products of root decay. Clay movement into transmission pores and fissures may block them, but may also stabilize their walls.

The length, density, and stability of fissures and pores depend on soil texture and mineral characteristics.

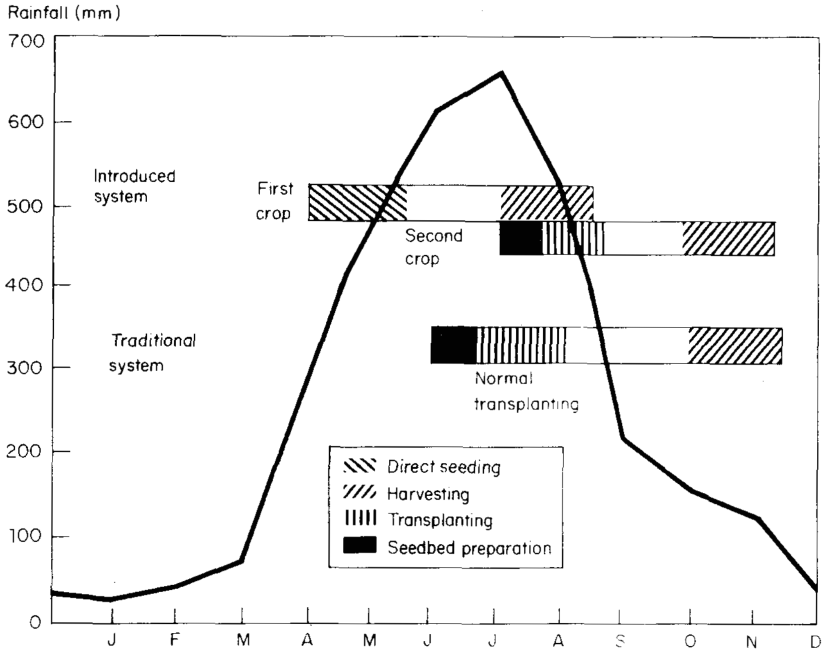


6. Porosity of a flooded rice soil after puddling (data of Dr. H. U. Neue, IRRI).

Heavy soils with 2:l lattice clays of large specific surface area tend to be cohesive, and form massive, cloddy structures when they dry after flooding. They also are easily puddled. Soils with low activity clay are less cohesive, more difficult to puddle, and have high percolation rates. Further studies are required to determine how best to manage such soils to develop appropriate drainage conditions.

STRUCTURAL CHARACTERISTICS AND CROP ESTABLISHMENT

Many soils that have been planted to rice have enough water for a dryland crop after rice. However, their seedbed structure usually is unsuitable, and dryland crops after rice often have low yields. Similarly, seedbeds may be difficult to establish for direct-seededrice at the onset of monsoon. Direct-seeding is becoming more widespread because short-duration rices now permit the growing of two rice crops in wet season (Fig. 7). Soil structure must be manipulated to allow easy crop establishment, rapid early growth to compete with weeds, and sufficient available water despite erratic early rains.



7. Timing of cultural practices in relation to rainfall in traditional single rice crop and direct-seeded rice - transplanted rice systems. Depending on the soil physical characteristics, it may be possible to establish a successful upland crop after the single or the second rice crop (From "An approach to rainfed farming: the Philippine case", Philippine Council for Agriculture and Resources Research and Development, and Bureau of Agricultural Extension).

Texture and mineralogy largely determine the soil structure after flooded rice. Cohesion between soil particles is determined by interparticle forces, which depend on the physicochemical properties of the particle surfaces, the ionic composition of the soil solution, and on organic materials associated with domains and microaggregates. A detailed literature review of factors determining soil structural behavior is given elsewhere (4).

Those soils with stable domains and microaggregates resist dispersion when cultivated in flooded conditions. They tend to behave like coarser textured soils (loams or sandy loams), are less cohesive, and dry to a granular structure. Establishing a dry-seeded crop in these soils is relatively simple. The cohesiveness of some soils with 2:1 lattice clays also can be reduced by organic matter. More information is needed about this phenomenon. Studies are needed also of the effects of Fe and A1 on flooded soil. There, these elements form organic complexes and influence clay flocculation and aggregation.

Soil animals also influence soil structure. Many soil animals cannot survive flooding: they therefore do not disturb soil physical consolidation after puddling, except in the few millimetres of aerated soil in contact with oxygenated water. More information is needed about animals that live in flooded soils and their effects on soil porosity.

Conventional tillage before a dryland crop after rice generally produces lower yield than if the crop is seeded using zero, minimum, or strip tillage, probably because less water is lost from an undisturbed soil (18). However, when rice is direct–seeded in soil moistened by early monsoon rains, tillage normally is essential to reduce weed competition.

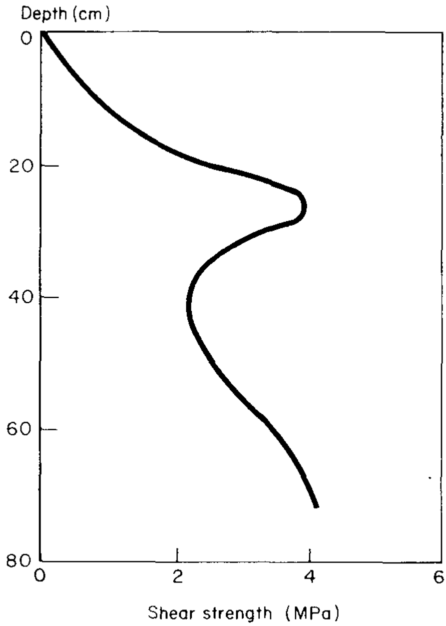
Traditionally, farmers wait until the rains saturate the land, then plow and harrow to puddle the soil, presumably maximizing weed destruction and perhaps allowing the soil to settle to a condition suitable for transplanting. Such land soaking often persists during several weeks when a crop could be growing; moreover, it appears to be very wasteful of water.

Puddling and its effects on soil structure have been widely studied. Destruction of transmission pores to reduce percolation is important in phreatic lands, but not in fluxial lands where the water table is at or above the surface. Puddling nevertheless is the normal practice on many fluxial lands, presumably because it reduces weed incidence, softens the soil for rapid transplanting, and allows levelling that helps control the depth and flow of surface water.

PANS, TRAFFICABILITY, ROOTING DEPTH, AND WATER STORAGE

Cultivating a wet soil always forms a pan. The pan layer may be denser, or may have higher clay content than the overlying soil because of clay dispersion and translocation during cultivation. The depth to the pan is related to cultivation method. Where rice has been grown for many years, the pan usually is readily apparent in the profile morphology. Even after short periods of cultivation, pans are easily detected with a cone penetrometer (Fig. 8).

The influence of pans on root development and soil trafficability is not clear. The relation between wet strength and root penetration suggests that pans hinder root development. However, there are varietal differences in the ability of roots to penetrate a compacted layer, and pan



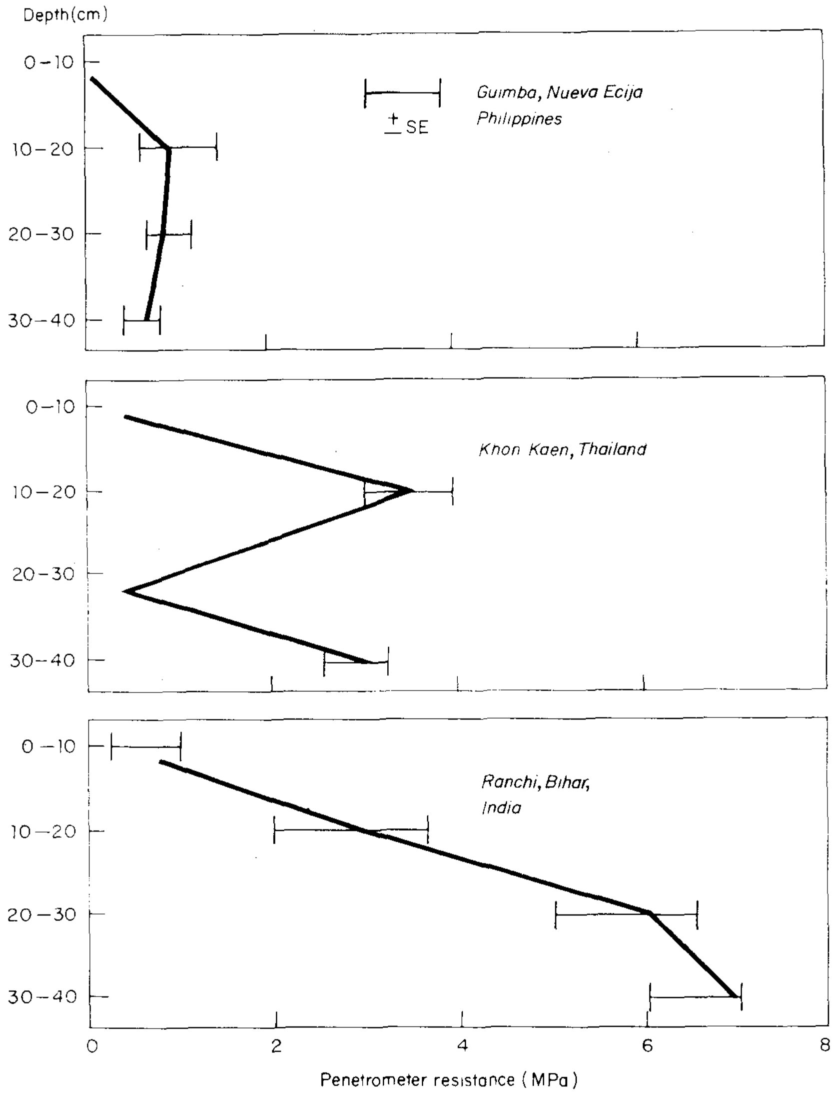
8. Resistance (shear strength) measured with a cone penetrometer for previously flooded soil at field capacity (data of S. G. Maghari and T. Woodhead).

strength differs considerably between soils and locations (Fig. 9). Puddling the surface soil should allow adequate root proliferation, provided the soil remains saturated; but it may also help create a pan that inhibits deep rooting.

Bearing strength is important during land preparation. Where the water table is perched, as in a pseudogley, and overlies an unsaturated soil, bearing strength may not be important. In stagnating and waterlogged areas, strength often is inadequate. In these latter areas, land preparation must be with low-pressure machinery or animals or manual. Draining or seasonal drying may improve soil consistency, but presently available information is not related to specific soil and drainage characteristics, and results cannot be generalized (4).

In rainfed and partially irrigated systems, the relations between water retention, soil strength, and root development are very important, particularly for rice, which has roots which usually cannot deeply penetrate a relatively dry soil. Soil water retention is important where rice is dry-seeded for early establishment or to avoid transplanting in more than 10-20 cm of water in deep water areas.

More data are needed on the effects of puddling on different soils. Specific information is needed on the loss of storage and transmission porosity, and on possibilities for tillage methods that could eliminate transmission pores but leave storage pores intact. Ghildyal (3) has vigorously



9. Different penetrometer resistance profiles for several Asian sites (9).

argued that soil compaction may be used instead of puddling. There may be certain soils for which compaction is the most suitable land preparation for rice.

CONCLUSIONS

Rice is the most important food crop in the developing world. About 90% of world production is harvested from the wetlands of Asia. Until now, production has kept pace with demand in most areas except Africa and the Middle East. But by 2000 at least 30% more rice production will be needed -- most of it from Asia, where there is little suitable land to expand the farming area. The increased production must therefore come from existing ricelands. Better rice varieties and increased use of fertilizers and organic manures will undoubtedly contribute to increased production, but their contribution will only be realized if soil physical properties are properly managed.

Water management is of primary importance. It will be necessary to develop new irrigation systems, and improve and expand existing systems. Estimates for the costs of such improvements and expansions have steadily increased and predictions for the systems' useful life have fallen. The usefulness for rice production of underdrainage and of increased water use efficiency has been questioned. It is therefore doubtful whether the proposed investments in new irrigation systems will be forthcoming.

Better water use and management can be encouraged by a better understanding of the physics of lowland soils. The pertinent research has received too little attention, as has research into soil cohesion, workability, and trafficability, which determine ease of cultivation and crop establishment. Studies also are needed of the processes of siltation of water distribution channels and reservoirs. Such siltation can considerably reduce the working life of an irrigation system.

Many rainfed ricelands are planted with dryland crops after rice. Crop establishment and management to ensure optimum use of residual soil water are critical. Understanding the relevant soil physical conditions could help increase production.

There are few physical scientists working with physical problems of wetland crop production. Much needs to be done to train senior and junior researchers so that rapid solutions may be found. Closer collaboration between the few scientists already studying wetland soil physical topics should help achieve sooner the needed solutions.

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INTERPRETING PHYSICAL ASPECTS OF WETLAND SOIL MANAGEMENT FROM SOIL TAXONOMY

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ABSTRACT

The guiding principles for developing the United States soil taxonomy classification system (published in Soil Taxonomy) were morphogenetic. However, parameters to define taxa were selected, wherever possible, on the basis of soil use. The taxa names allow several interpretations. This paper describes the relations of soil physical characteristics and management.

The soil taxonomy system does not reflect detailed surface soil characteristics. There is an urgent need to develop for wetland soil management a technical classification based on surface soil characters.

INTERPRETING PHYSICAL ASPECTS OF WETLAND SOIL MANAGEMENT FROM SOIL TAXONOMY

Wetland soil management aims to manipulate soil particles into configurations that retain water for the rice crop and promote extensive rooting, good aeration, and effective storage and release of water for dryland crops in a rice-based sequence. The soil to 25- to 50-cm depth is most important. The physical properties of this zone can be drastically altered through management, use, or misuse. Consequently, the physical properties are temporal. Other surface features, such as roughness, clod fragmentation, dispersion, and surface sealing, are transient properties. They are measurable and crucial to crop performance, but are unsuitable parameters for a classification system. Little has been done to evaluate and characterize them.

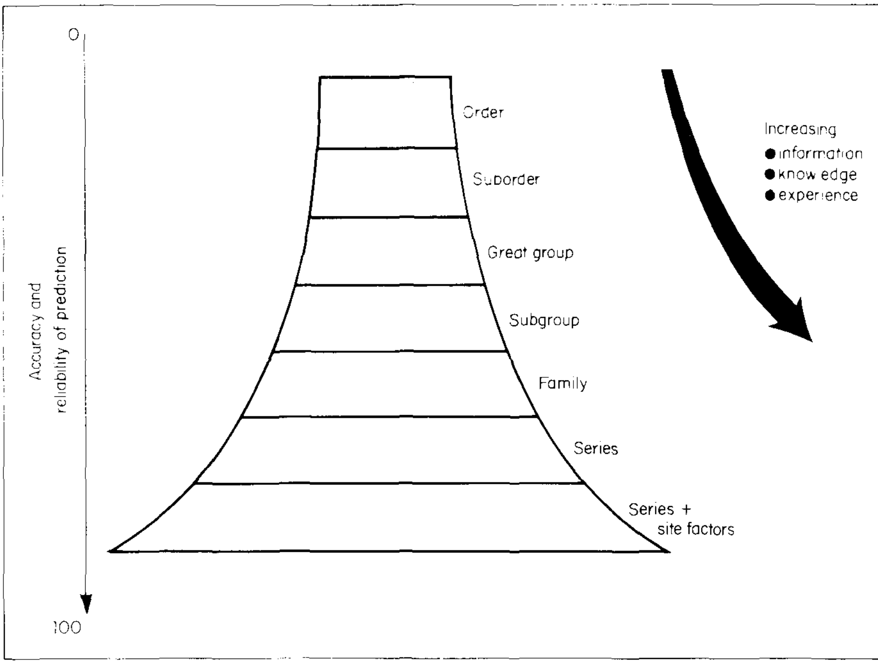
The United States soil taxonomy classification system (6) primarily addresses deeper layers with more permanent properties, but surface soil attributes are not completely ignored. For example, the definition of the argillic horizon requires a comparison with the clay content of the surface horizon. Some subsurface features, such as pans or other impermeable layers, directly or indirectly affect surface soil characterization.

This paper discusses some of the physical parameters used by Soil Taxonomy (6), and the rationale for selecting the differentiating criteria in relation to use and management of wetland soils. Sometimes, because of a lack of research or supporting data, criteria are arbitrary and were included in Soil Taxonomy by consensus favoring the criteria or their limits. The classification system will be refined over time.

SOIL TAXONOMY

Soil Taxonomy was developed to describe soils using objective criteria, to facilitate communication among soil scientists, and to enable the determination of soil response to management practices.

The system divides soils into hierarchical classes. The higher categories (Fig. 1) are abstract, with definitions based on genetic concepts. The lower categories are pragmatic and include properties relevant to soil use and management. The 10 orders, which are defined by major diagnostic



1. *Soil Taxonomy* categories in relation to information content and reliability of predictions of soil performance.

features, each relate to a substantial area of the world's soil (Table 1). The suborders are differentiated by factors that control major processes in the soil. Soil moisture and some temperature regimes are considered in most of the orders.

Table 1. Estimate of area of orders of soils in the world.

Soil	Land area (%)	Area (ha × 10^8)
Alfisols	13.2	17.1
Aridisols	18.8	24.4
Entisols	8.3	10.8
Histosols	0.9	1.2
Inceptisols	8.9	11.5
Mollisols	8.6	11.1
Oxisols	8.5	11.1
Spodosols	4.3	5.6
Ultisols	5.6	7.2
Vertisols	1.8	2.3
Soil in mountain areas	19.7	25.6
Miscellaneous	1.6	2.1

Diagnostic properties, or other major controls of genetic processes, are used to define the great groups. Subgroups are defined through important subordinate properties (Table 2). The family and series are the fifth and sixth categories of the system. They are distinguished by properties selected to create taxa that are successively more homogeneous for practical soil uses. Families provide classes with relative homogeneity in properties important to plant growth. Series are subdivisions of families that give the greatest homogeneity of properties in the root zone, but yet occur in sufficiently large areas that they may be mapped at scales used in detailed soil surveys. Figure 1 illustrates the increasing information content and accuracy of predictions as one moves from order to series.

Soil Taxonomy's nomenclature is one of its unique features. Each part of the name is taxonomic and also allows several interpretations. The properties available for interpretation increase toward the lower categories (4) (Table 3). The category of family gives groupings with specified ranges in

- particle size distribution in horizons of major biological activity below plow depth,
- mineralogy of the horizons,

Table 2. Relationships among categories in *Soil Taxonomy.*

Category	Basis for differentiation	Example of class name	Main features of the class
Order	Dominant soil process that developed soil	Ultisol	Clay accumulation; depletion of bases
Suborder	Major control of current process	Udult	Soil moist most of time; humid (udic) climate
Great group	Additional control of current process	Tropudult	Fairly constant soil temperature all year; tropical environment
Subgroup	Blending of processes (intergrades or extragrades)	Aquic Tropudult	Temporary wetness in rooting zone
Family	Internal features that influence soil-water-air relations	Fine loamy, mixed isothermic, Aquic Tropudult	Texture and mineralogy in a control section, and soil temperature
Series	Nature of materials that affect homogeneity of composition and morphology	Cerrada	Soil forming in weathering diabase

Table 3. Derived properties from soil names.

Category	Derived properties
Order: Oxisols	The soil has an oxic horizon. It has low CEC, traces of weatherable minerals, no rock fragments, and at least 15% clay.
Suborder: Ustox	The soil has an ustic soil moisture regime, indicating moisture stress during some of the year but not as severe as in the Torrox. Because it is not an Aquox, it is well drained; as it is not a Humox, it has a low organic carbon.
Great group: Acrustox	The soil has very low effective CEC and nutrient retention capacity. This and a possible high P fixation capacity are major constraints.
Subgroup: Typic Acrustox	The Typic subgroup implies a net positive charge and a high propensity to fix anions like phosphates.
Family: clayey, oxidic, isohyperthermic	The soil has more than 3.5% clay; the clay mineralogy is dominated by oxides and oxyhydrates. Soil tem-petature is high throughout the year.

- temperature regime,
- thickness of soil penetrable by roots, and
- other properties important for plant growth.

The response to management of comparable phases of all soils within a family are thought to be almost similar enough for most practical interpretations of such responses (1).

EVALUATING CONSTRAINTS TO MANAGEMENT

The derivation of soil properties from soil names is emphasized. Knowledge of these properties can be used to signal potential constraints or beneficial attributes of a soil. Table 4 illustrates some of the soil attributes that could be inferred from the prefixes used to develop the suborder and great group names in Soil Taxonomy. For example, in ACR UST OX:

OX indicates the order Oxisols,
UST is the prefix for suborder Ustox, indicating seasonal moisture stress, and
ACR is the prefix for the great group Acrustox, indicating high potential phosphate fixation and low nutrient holding capacity.

The inclusion of soil moisture and temperature regimes is an innovation in Soil Taxonomy. Soil moisture generally

Table 4. Formative elements in names of suborders and great groups and their general implications.

Formative element	General soil attributes
	For suborders
Alb	Pale and sometimes coarse textured
And	Anion retention, low bulk density
Aqu	High water table
Ar	Deeply plowed and mixed horizons
Arg	Presence of a finer-textured subsurface horizon
Bor	Low temperature is a constraint
Ferr	Large Fe mottles; some moisture saturation
Fibr	Poorly decomposed organic matter
Fluv	Stratified soil material
Fol	Undecomposed organic matter
Hem	Partially decomposed organic matter
Hum	Humus enriched
Ochr	Almost without organic matter
Orth	The typifying soil
Plagg	Man-made surface soil; soil is poor
Psamm	Sandy; low water and nutrient retention
Rend	Shallow soil on limestone
Sapr	Highly decomposed organic matter
Torr	Hot and dry; severe moisture stress
Ud	Low probability of moisture stress
Umbr	Acid; humus-rich surface horizon
Ust	Seasonal moisture stress
Xer	Moisture stress in hot season
	For great groups
Acr	Anion fixation; low nutrient holding capacity
Agr	With high biological activity; good medium for roots
Arg	Finer-textured subsurface horizon
Calc	Carbonates present
Camb	Usually a young soil
Chrom	Pale colors; low organic matter
Cry	Very cold; very short growing period
Dur	Impermeable duripan
Dystr, dys	Acid with possible Al problems
Eutr, eu	Base-rich environment
Frag	Root-restricting fragipan
Fragloss	As Frag with a fluctuating water table
Gibbs	Root-restricting sheets of gibbsite
Gyps	High gypsum content
Gloss	Fluctuating water table
Hal	Salt concentration; salinity
Hap1	Usually no problems
Hydr	May dry irreversibly
Luv	Leached

Continued on opposite page

Table 4 continued

Formative element	General soil attributes
Med	Cool climates
Nadur	Alkaline soil with a root-restricting layer
Natr	Alkaline conditions
Pale	Deep soil or has abrupt textural change
Pell	Dark soil with high humus content
Plac	Root-restricting placic horizon
Plinth	Soft red concretions with potential to harden irreversibly
Quartz	No weatherable minerals
Rhod	High P fixation
Sal	Saline conditions
Sider	High Fe; water stagnation
Sombr	Burried organic-rich horizon
Sphagn	Pal·tially decomposed organic soil
Sulf	Acid sulfate conditions
Trop	No temperature constraint
Verm	High biological activity
Vitre	Undecomposed volcanic material

is included at the suborder level, and sometimes at the great group and subgroup levels. Soil temperature is a defining criterion for the family level and sometimes is used at higher levels. A combination of soil temperature and moisture regime stratifies the environment into classes, the significance of which (5) is shown in Table 5. Some crops, particularly those bred to withstand certain soil constraints, may straddle class limits or move into another class.

Family

Soil particle size and mineralogical characteristics are used to distinguish families of mineral soils within subgroups. In Soil Taxonomy, families and lower categories, particularly series, serve largely pragmatic purposes. Family differentiae for mineral soils are the classes: particle size, mineralogy, calcareous or reaction, soil temperature, soil depth, soil slope, soil consistence, coatings (sands), and cracks. The differentiae are used where relevant; Soil Taxonomy gives the differentiae important for each order.

Soil Taxonomy defines particle size in relation to the entire particle size distribution of a soil, whereas texture refers only to the fraction finer than 2 mm. Table 6 lists

Table 5. Relation between crop and soil characteristics (5).

	Crops for each moisture regime				
Temperature regime	Aquic	Udic	Ustic	Xeric	Aridic
Thermic				Wheat Rice	
Hypel-thermic			Irrigated rice		Irrigated rice
Isohyperthermic	Flooded rice	Cassava Cocoyam Maize Upland rice Soybean Yam Beans	Irrigated rice Cassava Sorghum Pigeonpea Groundnut		Irrigated rice
Isothermic		Potato	Potato		
Isomesic		Potato Wheat	Potato Wheat		

Table 6. Particle-size classes for a family grouping.

1. **Fragmental.** Stones, cobbles, gravel, and very coarse sand particles, Too little fine earth to fill interstices larger than 1 mm.
2. **Sandy-skeletal.** Particles coarser than 2 mm are 35% or more by volume, with enough fine earth to fill interstices larger than 1 mm. The fraction finer than 2 mm is that defined for particle-size class 5.
3. **Loamy-skeletal.** Coarse fragments are 35% or more by volume, with enough fine earth to fill interstices larger than 1 mm. The fraction finer than 2 mm is that defined for particle-size class 6.
4. **Clayey-skeletal.** Coarse fragments are 35% or more by volume, with enough fine earth to fill interstices larger than 1 mm. The fraction finer than 2 mm is that defined for particle-size class 7.
5. **Sandy.** The fine earth includes sands and loamy sands, exclusive of loamy very fine sand and very fine sand textutes. Coarse fragments are less than 35% by volume.
6. **Loamy.** The fine earth includes loamy very fine sand, very fine sand, and finer textures with less than 35% clay. Coarse fragments are less than 35% by volume,
   - 6a. *Coarse-loamy.* Loamy particle size with 15% or more by weight fine sand (0.25-0.1 mm) or coarser particles, including fragments up to 7.5 cm, and with less than 18% clay in the fine earth fraction.
   - 6b. *Fine-loamy.* Loamy particle size with 15% or more by weight fine sand (0.25-0.1 mm) or coarser partrcles, including fragments up to 7.5 cm, and with 18 to 35% clay in the fine earth fraction,

Continued on opposite page

Table 6 continued

6c. *Coarse-silty.* Loamy particle size with less than 15% fine sand (0.25-0.1 mm) or coarser particles, including fragments up to 7.5 cm, and with less than 18% clay in the fine earth fraction. (Carbonates of clay size are not considered to be clay, but are treated as silt.)

6d. *Fine-silty.* Loamy particle size with less than 15% fine sand (0.25-0.1 mm) or coarser particles, including fragments up to 7.5 cm, and with between 18 and 35% clay in the fine earth fraction.

7. **Clayey.** Fine earth contains 35% or more clay by weight, and coarse fragments are less than 35% by volume.

7a. *Fine.* Clayey particle size with 35-60% clay in the fine earth fraction.

7b. *Very-fine.* Clayey particle size with 60% or more clay in the fine earth fraction.

In three situations, particle size names are replaced by other modifiers. Psamments and Psammaquents are by definition sandy soils, so a particle size class name is redundant. For soils with appreciable amounts of amorphous gels, such as Andepts and Andic subgroups, no particle size class is used. Particle size class names are not used if the organic content is high and particle size has little bearing on chemical and physical properties.

In the second and third of these situations, the following terms may replace particle size class names, and reflect and substitute for both particle size and clay mineralogy:

1. **Cindery.** More than 60% volcanic ash, cinders, and pumice by weight, and 35% or more by volume is 2 mm or larger, (Weight percentages are estimated from grain counts. Usually a count of one or two dominant size fractions of conventional mechanical analysis is enough to classify the soil.)
2. **Ashy and ashy-skeletal.**

   Ashy. 60% or more volcanic ash, cinders, and pumice by weight and less than 35% by volume is 2 mm or larger.

   Ashy-skeletal. Coarse fragments are 35% or more by volume and fine earth is ashy.
3. **Medial and medial-skeletal.**

   Medial. Less than 60% volcanic ash, cinders, and pumice by weight in the fine earth, less than 35% by volume is 2 mm or larger, and the fine earth fraction is not thixotropic. Dominated by amorphous material.

   Medial-skeletal. 35% or more of coarse fragments by volume, and the fine earth fraction is medial.
4. **Thixotropic and thixotropic-skeletal.**

   Thixotropic. Less than 35% by volume is 2 mm or larger, and the fine earth fraction is thixotropic.

   Thixotropic-skeletal. 35% or more by volume is coarse fragments, and the fine earth fraction is thixotropic.

the current particle size classes. Particle size classes in vertical sequences within a profile that differ significantly in pore size distribution, and hence substantially affect infiltration and water retention, are recognized as strongly contrasting. There are 44 such differential combinations. Examples are sandy over clayey, loamy-skeletal over fragmental, and fine-silty over sandy.

Assessing constraints from taxa

Table 7 shows some of the constraints that can be interpreted from soil taxa (2, 3). Similar tables can be constructed for all other taxa, and other limiting factors may be added. Such tables are guides for predicting potential constraints.

Physical aspects of soil management are less well indicated by soil names. Some few physical aspects are inferable from the taxa names for the following rice growing soils.

Entisols. In Entisols, the suborder with greatest potential use for flooded rice is Aquent. The most recent deposits, which have not yet ripened, are Hydraquents. They have an $\underline{n}$ value higher than 0.7, indicating very low bearing capacity. These soils occur on tidal flats and are subject to flooding. Like most Aquents, they are reduced and seldom dry.

Sulfaquents have sulfidic materials (essentially pyrite) within 50 cm of the soil surface. Drainage causes sulfuric acid formation and changes the salt concentration of the soil solution, thereby adversely affecting osmotic potential, As a result, crops may show drought symptoms although they are waterlogged.

Psammaquents are sandy soils with a high water table. They may be stratified but the strata are not contrasting enough to cause water perching or to have marked impact on permeability. Draining these soils can create moisture stress because there is no buffering effect on moisture content.

Tropaquents generally are confined to valley bottoms and may have a highly variable particle-size distribution.

Inceptisols. The Aquept suborder is the wet Inceptisol. Physical properties are similar to those of the great groups of the Entisols. The wetness stage is expressed in different ways:

Aquepts are very wet Inceptisols;

Typic Tropaquept wetness is from the groundwater table;

Table 7. Direct or inferred limiting conditions in selected Oxisols taxa.

Soil category in USDA Taxonomy	Direct or inferred limiting conditions[a]															
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Oxisols						X	X		X			X				
Aquox	X			X		X	X		X			X				
Gibbsiaquox	X			X		X	X		X			X				X
Plinthaquox	X			X		X	X		X			X				
Ochraquox				X		X	X		X			X				
Umbraquox				X		X	X		X			X				
Humox						X	X		X			X			X	
Acrohumox, Typic						X	X		X			X			X	X
Petroferric	X					X	X		X			X			X	
Gibbsihumox	X					X	X		X			X			X	X
Haplohumox						X	X		X			X			X	
Sombrihumox						X	X		X			X			X	
Orthox						X	X		X			X				
Acrorthox, Typic						X	X		X			X				X
Haplic						X	X		X			X				
Plinthic	X					X	X		X			X				
Eutrorthox, Typic						X			X			X				
Haplohumic						X			X			X			X	
Sombrihumic						X			X			X			X	
Tropeptic						X			X			X				
Gibbsiorthox, Typic	X					X	X		X			X				X
Haplorthox						X	X		X			X				
Aquic				X		X	X		X			X				
Epiaquic						X	X		X			X				
Plinthic	X			X		X	X		X			X				
Quartzipsammentic		X				X	X		X			X				
Tropeptic						X	X		X			X				
Ultic						X	X		X			X				

[a]X indicates presence of the constraint. A = root restrictive layer, B = texture, C = hydraulic conductivity, D = reducing conditions, E = moisture Stress, F = low CEC, G = high Al, H = acid sulfate, I = anion fixation, J = N mineralization, K = vertic properties, L = low mineral content, M = carbonates, gypsum, N = salinity, alkalinity, O = soil temperature, and P = type of charge.

Aeric Tropaquept wetness is confined to the upper part of the soil because of a perched water table, indicating an impermeable layer;

Aquic Dystropepts are moderately well-drained soils; and

Typic Dystropepts are well-drained soils.

The best-drained Inceptisols are the Tropepts and the Ochrepts -- the latter being nontropical. The three great groups of Tropepts on which rice is grown are the Humitropepts, Ustropepts, and Dystropepts. A water table in the lower part of these soils is identified by the aquic subgroups. The Ustotropepts are the most drought-prone because their moisture control section is dry or partly dry for at least 90 cumulative days in a year. Depending on the textural family, the surface soil can be puddled for one rice crop in rainy season. Rice followed by a dryland crop or fallow is the normal cropping system. The other Tropepts can be planted with more than one rice crop each year.

<u>Vertisols</u>. Vertisols have adverse physical properties. By definition, they have at least 30% clay, and that clay is dominated by montmorillonite. The mineralogy causes high shrink-swell potential, and the soils are deeply cracked when dry and have very low workability when wet. When dry, surface clods are hard or very hard, and growing an off-season crop requires carefully timed land preparation.

Most Vertisols are moisture-saturated in parts of the profile sometime in the year. Puddling requires more effort than for Aquepts or Aquents. Moreover, because of their cracking properties, Vertisols do not form plow, traffic, or dasyk pans.

<u>Mollisols</u>. Mollisols have a mollic epipedon. They generally have the best tilth conditions of all orders. The mollic epipedon or surface horizon cannot by definition be hard or very hard when dry, and therefore is optimal for tillage. The Aquolls and Aquic subgroups are wet Mollisols. Many of these soils have few physicochemical constraints for crop production.

<u>Ultisols and Alfisols</u>. Ultisols and Alfisols have a subsurface horizon with a clay accumulation. This argillic horizon has good moisture and nutrient storage capabilities. The surface horizons are light textured and encourage root penetration.

The Aquults and Aqualfs are wet Ultisols and Alfisols. They have a groundwater table or sometimes a perched water table. Examples are the Albaquults or Albaqualfs. They are used for rice cultivation and pose few physical constraints.

The better drained Ultisols and Alfisols are planted to rice, as in Thailand. Puddling and retaining water are sometimes difficult. Farmers try to create a pan, generally just above the argillic horizon, that perches the water. This can take several years, and crop failure from drought in the first years is a recurring problem. Sustaining a wetland crop on these soils requires much more water because of high percolation.

Oxisols. Management of Oxisols is similar to that of Ultisols and Alfisols. Some wet Oxisols have plinthite, which if close to the surface can harden irreversibly to iron-stone. These soils are rare.

Some Oxisols (and Ultisols) have a petroferric contact that is an impermeable layer of iron-stone. The thickness of soil material above the contact determines the use of the soil. The contact causes water to perch, and rice may be grown in wet season.

Histosols. Subsidence and chemical constraints are the greatest problems in the organic Histosols. In many tropical Histosols, logs and other partially decomposed plant materials inhibit land use.

Aridisols. Moisture availability is the greatest crop constraint of Aridisols. If irrigation is available, however, some of these soils can be cropped as wetland soils. Salinity or alkalinity is a recurring problem in most Aridisols, and also may cause physical problems.

Within specific limits, sodium concentration induces clay migration. The clay accumulates at specific depths and forms a natric horizon. In soils where the horizon is well developed, hydraulic conductivity is very low, and water can perch for long periods.

CONCLUSIONS

Taxa development in Soil Taxonomy was guided by morphogenetic principles but, wherever possible, the parameters that define taxa or classes have been criteria important to soil uses. Thus, useful interpretations can be inferred from taxa names. Most management information is presented at the level of soil series or of phases of the series.

The system has not been rigorously tested in tropical wetland conditions. Because the system is morphogenetic, surface soil characteristics, which are so critical to crop performance, receive least attention. There is much to be learned of them. From these properties, a technical classification could be developed for rice soils.

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EVALUATION OF THE PHYSICAL ENVIRONMENT FOR RICE CULTIVATION

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ABSTRACT

This paper discusses climate, landscape, and soil conditions for unbunded rainfed rice, bunded rainfed rice, rice grown under natural flooding, and irrigated rice.

Climatic parameters include growing season, mean rain–fall, mean temperature at crop development and ripening stage, maximum temperature of the warmest month, average sunshine duration, and relative humidity at different crop stages. Landscape is discussed in terms of slope and micro–relief.

Methods of classifying natural flood conditions and drainage are suggested. Soil characteristics are grouped by physical and fertility parameters and by saline and alkaline conditions. The parameters are quantified and classes are suggested for the major types of rice cultivation.

EVALUATION OF THE PHYSICAL ENVIRONMENT FOR RICE CULTIVATION

The Food and Agriculture Organization (FAO) (1) defines land utilization by crop and management level, farm size, capital input, and farmer know–how.Rice cultivation techniques can be grouped by broad land utilization patterns. In this paper we discuss unbunded rainfed rice, bunded rainfed rice, rice grown under naturally flooded conditions, and irrigated rice.

Most unbunded rainfed rice is cultivated like other cereals -- under dryland conditions without flooding. For bunded rice, which often is grown on terraced lower and moderate slopes, land is levelled and puddled. Most water is from rainfall accumulation within the bunded fields, but nearby springs may provide supplementary water.

Rice cultivation on naturally flooded land predominates in many countries. The rice is transplanted into the puddled floodplain soil. Irrigated rice is grown under fully controlled irrigation, and can be grown in hot, dry climates.

For each water regime there are specific cropping requirements based on landform, flooding, and soil physical characteristics. In the FAO system (1) used here, land characteristics are quantified at class level. Class is the most important limitation level, and the evaluation is thereforequalitative.

The system classifies land as

Order S. Suitable land.
- Class S1. Suitable.
- Class S2. Moderatelysuitable.
- Class S3. Marginallysuitable.

Order N. Unsuitable land.
- Class N1. Actually unsuitable but potentially suitable.
- Class N2. Actually and potentially unsuitable.

CLIMATE

Rice grows only in warm climates on land with sufficient water supply (Table 1). The major rice producing countries are between 30°N and 30°S. Exceptions are Japan and Korea. In the tropical and subtropical regions, rice is the most productive cereal. It is grown in Asia on land from below sea level to 2,700 m elevation.

Table 1. Agroclimatic evaluation for rice cultivation.

Climate characteristics	Agroclimatic land class[a]				
	S1	S2	S3	N1	N2
Mean rainfall (mm) for rainfed rice during growing season	> 1,400	> 1,000	>800	<800	<800
Mean temp at crop development stage (°C)	24-36	18-42	10-45		any
Mean temp at ripening stage (°C)	25-38	20-42	17-45		any
Mean minimum temp at ripening stage (°C)	17-25	10-28	7-30		any
Average daily maximum temp, warmest month (°C)	30-40	26-45	21-50		any
Relative humidity at tillering (%)	55-90	any			
Relative humidity at vegetative stage (%)	50-90	any			
Relative humidity for rainfed rice after milk stage (%)	40-90	> 30	< 30		
Relative humidity at harvest (%)	< 60	< 80	> 80		
Growing season sunshine duration	>0.75	>0.45	< 0.45		

[a] S1 = suitable land, S2 = moderately suitable, S3 = marginally suitable, N1 = actually unsuitable but potentially suitable, N2 = actually and potentially unsuitable.

Although considered a tropical crop, rice is extensively grown in subtropical and low temperate latitudes. It can grow almost anywhere that average temperature exceeds 20°C, and minimum temperature exceeds 10°C for 4 — 6 mo. Rice needs generous rainfall or irrigation.

Rainfall

In many tropical countries, rice growing areas receive high rainfall. With 1000 to 1400 mm of evenly distributed rainfall, rice can grow as an upland crop without standing water, or on level, bunded fields that have standing water for most of the season. Sometimes rice can grow in these conditions with only 800 mm of rainfall during the growing season. On naturally flooded or irrigated lowlands, rainfall is not a constraint.

Temperature

Rice grows well when mean temperature varies between 20 and 38°C, with ideal temperatures between 30 and 32°C. Warm temperatures at germination promote faster growth and earlier flowering. Performance is marginal if temperature is above 42 or below 18°C. When maximum, mean, and minimum temperatures are lower than 25–26°C, 21–22°C, and 17°C, the percentage of ripened grains decreases rapidly. Ideally, the mean temperature at ripening is 30 to 33°C.

Most data on temperature and rice growth are from controlled, glasshouse experiments. Little information is available for natural conditions. Results from controlled low temperature experiments have been successfully extrapolated to natural conditions. For high temperatures, glasshouse studies do not always agree with those in natural conditions, probably because field temperatures are actually higher than those in meteorological screens.

Relative humidity

Relative humidity may affect grain formation after milk stage, ripening, and disease incidence. High relative humidity favors crop growth through the vegetative stage. During grain formation, low humidity may cause grain to shrink, but high humidity favors disease, particularly in rainfed rice.

Radiation intensity and sunshine duration

Radiation intensity influences potential yield, and where it is not measured, it can be determined approximately from the fraction of actual to maximum possible sunshine hours.

LANDFORM

Evaluation of slope and landform for rice cultivation depends on the type of rice culture.

For upland rice, slope criteria are similar to those for other cereals, but may depend upon management practices. For intensive management, land should be flat or have long, regular, smooth, 2–4% slopes. Four percent is recommended only for heavier soils. Gentle slopes permit a wide choice of field design, and economical cultivation and harvesting techniques. Slopes greater than 8% severely limit rice cultivation. With low management on small fields, rice may grow well on slopes up to 8%, and marginally on 16 to 30% slopes.

For bunded rice, fields must be levelled. In deep soils, 10- to 20-m basins can be built on slopes up to 4%. Eight to 12% slopes are marginal. Slope influences available soil depth because terracing cuts may expose impermeable substrata.

Naturally flooded rice requires level ground. Even slight slopes require some bunding to control floodwater and to maintain uniform field water depth. Usually, flooded rice is grown on naturally flat land.

For irrigated, intensive rice farming, land should have less than 1% slope so uniform water depth can be maintained. A slight slope helps water distribution. Irrigated rice can be grown on slopes up to 4%, but levelling is required for optimum yields. Levelling and the consequent water distribution requirements may restrict field size.

MOISTURE REGIME

Moisture regime is determined by flooding and drainage. Drainage also determines soil oxidation–reduction potential, which affects rice growth and yield. Some drainage or lateral water movement generally is desirable to prevent excessive soil reduction and consequent undesirable chemical changes. Poorly drained, heavy soils become strongly reduced, while lighter, better–drained soils may retain an oxidizing root zone for long periods. Sometimes, sandy soils produce superior yields, but excessive drainage can use too much water and waste applied fertilizers.

Flooding influences soil redox potential, which also depends on soil depth, organic matter content, and ion balance. Sometimes an oxidized horizon may occur because air is trapped in the soil by flooding. Nitrate is the first nutrient to become reduced after flooding, and nitrate is lost from the soil mainly through denitrification.

Moisture regime, as determined by drainage and duration and depth of flooding, vary for different systems of rice cultivation. Flood duration can be classified in relation to the length of the rice–growing season (Appendix 1):

1. flood duration is shorter than the minimum growing season,
2. flood duration is near the minimum growing season,
3. flood duration equals the optimum growing season,
4. flood duration exceeds the optimum growing season and the crop must be harvested from flooded fields.

Flooding depth (Appendix 1) is classified as:

1. less than ideal,
2. ideal,
3. more than ideal, but permits growing common rices,
4. marginal for growing common rices and floating rices are recommended,
5. too deep for all but floating rices.

In addition to flooding depth, irregular, sudden increases in flood level may influence the suitability of land for rice cultivation. Upland and bunded rice are considered to be grown as upland crops on land not susceptible to flooding.

Table 2 summarizes the flood classes and indicates the land class of highest capability for different types of rice cultivation. Drainage class (Table 3) also determines the highest capability that land may have for rice culture. For upland rice, drainage classes are similar to those used for other cereals.

Cultivation of rainfed bunded rice usually is in valley hollows and on lower slopes where drainage often is poor. This imperfect drainage helps retain water and creates optimal conditions for bunded rice.

Similarly, for irrigated rice, imperfect drainage and moderately well–drainedsoils seem ideal. Water uplift will be slight and drainage at harvest is easy. Only very poorly drained soils are considered marginal (S3) because of difficulties of flood control, drainage, and secondary salinization.

This evaluation of drainage classes for rice cultivation is tentative, and is made realizing that there are probably relations between drainage and flood classes.

PHYSICAL AND CHEMICAL SOIL CONDITIONS

Standing water must be maintained for wetland rice cultivation. Soil texture and structure and the presence of shallow

Table 2. Highest capability of land class for rice cultivation[a] as related to depth and duration of flooding[b] for natural floods (A) and for irrigated conditions (B).

Flood depth	Highest capability land class for rice at indicated flood duration											
	1			2			3			4		
		A	B		A	B		A	B		A	B
1	F11	N2	S1	F21	S3	S1	F31	S1	S1	F41	S2	S2
2	F12	N2	S1	F22	S3	S1	F32	S1	S1	F42	S2	F2
3	F13	N2	S2	F23	S3	S2	F33	S2	S2	F43	S3	S3
4	F14	N2	S3	F24	S3	S3	F34	S3	S3	F44	N2	N1
5	F15	N2	N1	F25	N2	N1	F35	N2	N2	F45	N2	N2

[a]S1 = suitable land, S2 = moderately suitable, S3 = marginally suitable, N1 = actually unsuitable but potentially suitable, N2 =actually and potentially unsuitable. [b] F32 = flood duration 3, flood depth 2, etc; Fo = no floods.

Table 3. Highest capability of classes[a] in relation to drainage.[b]

Drainage class	Unbunded rainfed		Bunded rainfed	Naturally flooded	Irrigated
	A	B			
Good	S1	S3	S3	N2	S2
Moderate	S2	S2	S2	S3	S1
Imperfect	S3	S1	S1	S2	S1
Poor	N1	N1	S2	S1	S2
Very poor	N1	N2	N2	S2	S3

[a]S1 = suitable land, S2 = moderately suitable, S3 = marginally suitable, N1 = actually unsuitable but potentially suitable, N2 =actually and potentially unsuitable. [b]A = fine loamy and clayey families, B = coarse loamy and sandy families

groundwater determine whether standing water can be easily maintained on a field.

Naturally flooded rice usually is underlain by shallow groundwater during flooding and can be cultivated on a wider soil textural range than irrigated rice grown on soils without shallow groundwater. On these latter soils, infiltration rate is influenced mainly by texture and structure.

For soil management, surface texture is more important than subsurface texture. Surface soils with predominantly coarse fragments are difficult to puddle. Surface stoniness can limit mechanization. Land evaluation criteria for different rice cultures are suggested in Tables 4, 5, 6, and 7.

Soil depth also should be considered. Depth is most important in bunded rice where levelling may expose impermeable substrata or barren saprolite on steeper slopes.

In arid areas, calcium carbonate content affects soil physical and chemical characteristics. High lime concentration may not severely restrict water movement, but can prevent root penetration. Rice is moderately tolerant of soil calcium carbonate: a content of 25-30% is marginal for rice growth.

When gypsum is present in hot, dry areas it affects the cation balance of the soil. Because it is easily soluble, it releases Ca and may disturb Ca:Mg and Ca:K. It also improves soil structure and prevents sodium saturation. Up to 3% gypsum content serves as a plant nutrient and favors rice growth. Root zone gypsum content higher than 15% limits growth.

Table 4. Land classes for rainfed unbunded rice.[a]

Land characteristics	Landclasses				
	S1	S2	S3	N1	N2
Climate (C)	According to separate evaluation				
Topography (t)					
% slope (1)	<4	<8	< 16	< 25	> 25
(2)	<8	< 16	< 30	< 30	> 30
Wetness (w)					
Flooding	none	none	none to slight	none to slight	any
Drainage(3)	good	moderate or better	imperfect or better	poor or better	very poor or better
(4)	imperfect	imperfect or moderate	good, moderate, or imperfect	poor or better	very poor or better
Physical soil characteristics (s)					
Surface texture/structure (x)	C-60v to L	C+60v to LfS	C+60v to cS	C+60v to cS	Cm to cS
Surface coarse fragments (%)	< 15	< 35	< 55	< 55	>55
Surface stoniness, m apart	>100	> 30	> 10	>1.5	any
Rockiness (%)	0	<2	< 10	<10	>10
Subsurface texture (x)	Co to SCL	C+60 to LfS	C+60v to fS	C+60v to fS	Cm to cS
Subsurface coarse fragments (%)	<35	< 55	< 55	< 55	> 55
Depth to impermeable layer (cm)	> 90	> 50	> 20	> 20	< 20
$CaCO_3$ (%)	<6	< 15	< 25	< 25	> 25
Fertility limitations (f)					
Apparent CEC (meq/100 g)	> 16	>0, -charge	>0, +charge or −charge		
Base saturation (%) (0-15 cm)	> 50	>35	<15		
Organic carbon (%) (5) (0-15 cm)	> 1.5	>0.8	<0.8		
(6)	>0.8	< 0.8			

[a](1) Intensive fully mechanized agriculture, (2) Primitive farming, (3) Fine loamy or clayey families, (4) Coarse loamy and sandy families, (5) Soils with low activity clays, (6) Calcareoussoils. (x) For textural sequence, refer to Appendix II.

Table 5. Land classes for rainfed bunded rice.

Land characteristics	Landclasses				
	S1	S2	S3	N1	N2
	Same as rainfed upland rice, except for:				
Topography (t)					
Slope (%)	0-4	4-8	8-12	12-25	> 25
Wetness (w)					
Flooding	Fo to F32	Fo to F42	Fo to F43	Fo to F44	Fo to F45
Drainage	imperfect	poor to moderate	poor to good	poor to good	very poor to good
Physical soil characteristics (s)					
Surface texture	Cm to SiCs	Cm to Si	Cm to SC	Cm to SC	Cm to cS
Surface coarse fragment (%)	none	<15	< 35	<35	> 35
Subsurface texture	Cm to Si	Cm to SC	Cm to LfS	Cm to LfS	Cm to cS
Subsurface stoniness (%)	none	< 15	< 35	< 35	>35

Note: Depth to be considered after levelling and grading. Flood sequence as for irrigated rice.

Table 6. Land classes for rice cultivation under natural floods. [a]

Land characteristics	Landclasses				
	S1	S2	S3	N1	N2
Topography (t)					
Slope (%)	no	<2	<4	<6	>6
Wetness (w)					
Flooding	F32-F31	F32 to F42	F32 to F24	F32 to F24	F32 to Fo
Drainage	poor	very poor to imperfect	very poor to moderate	very poor to moderate	very poor to good
Physical soil conditions (s)					
Surface texture	Cm to SiCs	Cm to SCL	Cm to fS	Cm to fS	Cm to cS
Surface coarse fragments (%)	<15	<35	<55	<55	>55
Surface stoniness					
Rockiness					
Subsurface texture	Cm to LfS	Cm to cS			
Subsurface coarse fragments (%)	<35	<55	>55		
Depth to impermeable layer (cm)	>90	>50	>20	>20	<20
$CaCO_3$ (%)	<6	<15	<25	<25	>25
Gypsum (%)	<3	<10	<15	<15	>15
Fertility limitations (f)			As in Table 4		
Salinity and alkalinity (n)					
EC (mmho/cm on saturated extract)	<2	<4	<6	<6	>6
ESP(%)	<20	<30	<40	<40	>40

[a] Flood sequence: F32-F31-F33-F41-F42-F34-F22-F21-F23-F43-F24-F44-F35-F25-F45-F11-F12-F13-F14-F15-Fo (for definition of flood classes - see Table 2).

Table 7. Land classes for irrigated rice.

Land characteristics	Land classes				
	S1	S2	S3	N1	N2
Topography (t)					
Slope (%)	<1	<2	< 4	< 6	> 6
Wetness (w)					
Flooding	Fo to F32	Fo to F42	Fo to F43	Fo to F44	Fo to F45
Drainage	moderate to imperfect	good to poor	good to very poor		
Physical soil conditions[a] (s)					
Surface texture (1)	Cm to SiCs	Cm to Si	Cm to SC	Cm to SC	Cm to cS
(2)	Cm to SiCs	Cm to SCL	Cm to fS	Cm to fS	Cm to cS
Surface coarse fragments (%) (1)	no	< 15	< 35	< 35	> 35
(%) (2)	< 15	< 35	< 55	< 55	> 55
Surface stoniness					
Surface rockiness					
Subsurface texture (1)	Cm to Si	Cm to SC	Cm to LfS	Cm to LfS	Cm to cS
(2)	Cm to LSf	Cm to Sc			
Subsurface coarse fragments (%) (1)	no	< 15	< 35	< 35	> 35
(%) (2)	< 35	< 55	> 55		
Depth to impermeable layer (cm)	> 90	> 50	> 20	> 20	< 20
$CaCO_3$ and gypsum as in Table 6					
Fertility requirements as in Table 4					
Salinity and alkalinity as in Table 6					

[a] (1) Soils without groundwater within a depth of 30 cm from the surface (same as bunded), (2) soils with groundwater near or at the surface (same as under natural floods). Flood sequence: Fo-F11-F12-F21-F22-F31-F32-F13-F23-F33-F-42-F14-F24-F34-F43-F15-F25-F44-F35-F45.

SOIL FERTILITY

The most important soil characteristics related to natural fertility are weathering as expressed by cation exchange capacity, base saturation, and organic matter content. At a certain level of generalization, these characteristics can be deduced from family-level taxonomic soil classifications. For land class evaluation for rice, fertility categories are listed in Table 4.

Many rice soils have pH between 4.5 and 6, but some are alkali. However, the pH of lowland puddled rice soil may not be reliably derived from dry soil samples. When soil is flooded, the soil solution is in equilibrium with floodwater and takes its pH. Sys and Riquier (2) suggest that pH 5.5-7.5 is optimum for rice. pH lower than 5.2 and higher than 8.2 are marginal for rice growth.

SALINITY AND ALKALINITY

Rice is sensitive to salinity. It will not grow when salinity expressed as conductivity of the saturated extract is higher than 6 mmho/cm. Salinity of 4 – 6 mmho/cm is marginal. Less than 2 mmho/cm is optimal.

In contrast, rice tolerates high alkalinity. Yield is not affected at 10-20% sodium saturation, but is decreased at 30 to 40% saturation. Table 6 shows the values for conductivity and exchangeable sodium percentage that may be used in riceland evaluation.

REFERENCES CITED

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2. Sys, C., and J. Riquier. 1979. Ratings of FAO/UNESCO soil units for specific crop production. Report on the second FAO/UNESCO expert consultation on land resources for populations of the future. Appendix II, pp. 55-95. FAO, Rome.

APPENDIX 1

Tentative classes for duration of floods

Class	Duration range (mo)
1	<2
2	2–3
3	3–4
4	>4

Tentative flood depth classes

Class	Depth range (cm)
1	<10
2	10–20
3	20–40
4	40–80
5	>80

APPENDIX 2

Textural-structural range

Cm	clay massive
SiCm	silty clay massive
C+60v	clay with more than 60% clay fraction on vertisol structure
C+60s	clay with more than 60% clay fraction and a strong to moderately developed blocky structure
SiCs	silty clay, structured
Co	clay with weak structure and consistence of the oxic horizon
SiCL	silty clay loam
CL	clay loam
Si	silt
SiL	silt loam
SC	sandy clay
L	loam
SCL	sandy clay loam
SL	sandy loam
LfS	loamy fine sand
LS	loamy sand
LcS	loamy coarse sand
fS	fine sand
S	sand
cS	coarse sand

SOILS ON WHICH RICE-BASED CROPPING SYSTEMS ARE PRACTICED

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ABSTRACT

About 90% of the world rice area is in South and Southeast Asia, mainly in marine and fluvial lowlands. A few major landforms include most soils on which wetland rice is traditionally grown. In marine lowlands, the landforms are rapidly aggrading coastal plains and slowly aggrading or stationary coastal plains. In fluvial lowlands, rice grows in inland valleys, on alluvial fans and fan complexes, in meander floodplains, and on (recent and older) river terraces. In this paper, the most common rice soils are typified using Soil taxonomy, which classifies soils by inherent and stable properties. Appropriate land use-induced soil properties are briefly mentioned. Regional distribution of rice soils is discussed in terms of typical physiographic settings. The paper concludes with a figure where the most common rice soil suborders for each landform are arranged by degree of pedogenetic development.

SOILS ON WHICH RICE-BASED CROPPING SYSTEMS ARE PRACTICED

This paper describes the major landforms and soils on which lowland rice is grown. Eighty-nine percent of rice is grown south and east of the Himalaya Mountains, mainly between 70 and 150 E and 10 S and 40 N. The rest is in equatorial Africa and the Mediterranean region (4%) and in the Americas (7%), roughly between 30 S and 30 N. Between 20 S and 20 N, rice will grow all year if there is enough water (5, 6, 9). Most rice is grown on level lowland alluvial deposits in river basins and contiguous coastal plains that are periodically waterlogged and receive more than 1,000 mm annual rainfall. About one-third of all riceland is irrigated, making it possible to user drier and/or steeper land for rice cultivation and to intensify land use where crop performance would otherwise be limited by water stress.

Within its temperature zone, rice can thrive on almost any soil if there is enough water for periodic inundation of the land. Thus, rice-based cropping systems are associated with landscape features rather than soil properties. We briefly discuss major landforms of rice-growing areas before providing a taxonomic characterization of common rice soils.

MAJOR LANDFORMS IN RICE-GROWING AREAS

Most rice-growing areas are associated with present or past alluvial deposition. Several authors (7, 9) have successfully grouped most rice areas in a few elementary landforms. In marine landscapes, the landforms most frequently associated with rice-based cropping systems are rapidly aggrading coastal plains and stationary or slowly aggrading coastal plains. In fluvial landscapes, they are inland valleys, river fans and fan complexes, river floodplains, and river terraces.

A brief discussion of the geogenesis of marine and fluvial landscapes will help place their landforms and soils in proper perspective.

Marine landscapes

The geogenesis of marine lowlands began in the Pleistocene Era when sea level changes, concurrent with glacial and interglacial periods, caused large fluctuations in erosion and sedimentation. Verstappen (12) estimated that rainfall in today's tropics was 30% lower in glacial periods and that temperatures were 3 to 5 K lower. The drier, cooler conditions made vegetation generally less luxuriant. The lower erosion base of the rivers and the sparse savannah-like vegetation encouraged physical weathering of hinterlands and formed large areas of coarse-textured old alluvium on top of the Tertiary land surface.

After the last regression, which ended about 11,000 yr ago, the seas rose slowly to their present level which stabilized about 5,400 years ago (1). As temperature and rainfall increased, chemical weathering of rocks intensified and sediments became finer. While the sea level was still rising, this sedimentation probably did not lead to wide-scale accretion of coastal land. There is pedological and other evidence that, in many regions, sedimentation barely kept up with the rising sea; shorelines therefore remained stable or shifted very slowly. Accretion of coastal floodplains accelerated only after the sea level stabilized.

This general pattern was worldwide, but there were local exceptions. Where a deep trench occurs near the shore as a consequence of plate tectonics, as near the Sunderbans in Bengal and Bangladesh, further accretion of coastal land is impossible. Local tectonic movements and differences in the intensity of tidal fluctuations also interfere with accretion or can lead to coastal abrasion.

It is important to realize that river gradients decrease while coastal accretion progresses. The low gradient of rivers traversing extensive coastal plains is associated with wide, shallow river beds and low stream velocity. Such rivers carry only a low bedload of fine-grained material. Consequently, sedimentation rates decrease with progressing accretion. This also is why rivers on extensive coastal lowlands have low, fine-textured, vaguely defined levees.

Accretion may be rapid where rivers incise Pleistocene alluvium or older formations close to the shoreline. Most coastal ricelands are recent aggrading plains traversed by small and large rivers. Because of variations in sedimentation, consecutive coarser-textured former beach ridges sometimes occur but the plains are otherwise silty or clayey and flat. Apart from tidal fluctuations, which affect water movement near the shore or at most a few kilometres from creeks and rivers, the swampy basins between rivers are stagnant.

In the equatorial zone, inland parts of such basins often are covered with freshwater peat under dense swamp-forest vegetation. On the seaward side, the plains are seamed by narrow mangrove belts that shift with the coastline. Where aggradation is slow or absent, for example as a consequence of low river sediment loads, a wide, dendritic tidal creek system can develop, and mangroves colonize vast tracts of land. Remnants of the Pleistocene alluvial complex still are intact in places, but they are much less important rice areas than the Holocene floodplains.

Fluvial landscapes

A fluvial landscape, in our context, is an aggregation of landforms within a watershed. By following a river from the source toward its mouth, one often can identify one or more of the following landscape components: inland valley, river fan or fan complex, the meander floodplain, and remains of a former river floodplain (river terrace).

Most major rivers begin in hilly or mountainous inland areas where drainage gullies collect excess precipitation from adjacent hillsides. As more and more gullies converge, erosion and redeposition of soil material form a true river bed. If the drainage base is sufficiently low, the river incises deeply into the land to form an inland valley. The physiographic appearance of inland valleys cannot be detailed here because there are wide variations in characteristics due to inequalities of terrain slope, composition and structure of rock formations, kind and intensity of weathering, soil detachment, erosion, etc. However, most inland valleys have flat bottomlands with soils that reflect the mineralogy of adjacent drylands in their parent material, but otherwise have characteristics that developed under the specific hydrologic regime of the valley. Large areas of recent and very recent valley bottom soils are planted to rice.

River fans form where rivers leave the uplands. The abrupt transition from a narrow, inland valley stream bed to a wide bed or complex of stream channels causes a sudden drop in river flow velocity and transportable bedload. Thus, induced sediment deposition by one or more regularly shifting stream channels forms a classical alluvial fan with coarse-textured sediments near the apex, becoming gradually finer toward the base as slopes become gentler and floods less irregular. A fan complex or piedmont plain forms where adjacent fans overlap. Rice is grown on many alluvial fans and piedmont plains, particularly on the fine-textured lower parts.

Meander floodplains are most common along the middle and lower tracts of rivers. Some of the floodplain is occupied by the river bed and adjacent levees but, normally, most of it consists of low, wet basins with relatively fine-textured hydromorphic soils. As meandering rivers gradually change course, basin areas often include remnants of former levees and riverbeds that are wholly or partly filled with later sediments. Lacustrine conditions may prevail. River basins are traditional rice–growingareas, and the higher parts of present and former levees are commonly planted to dryland crops or used as dwelling sites.

A sharp lowering of a floodplain's base level of drain–age, for example by orogenetic land lifting or a drop in sea level, causes the river to cut into the existing floodplain. Accelerated erosion and redeposition will form a new complex of levees and basins at a lower elevation, but remnants of the former floodplain may remain intact to form alluvial terraces. Nearly all major rivers have alluvial terraces, and they represent a large area of world riceland.

TAXONOMIC INVENTORY OF RICE SOILS

Soil formation is influenced by differences in physiography and age of landform. It is therefore logical to base a first inventory of soils on properties that are a recognizable consequence of soil history in a certain physiographic set–ting. As taxonomic discriminators, such inherent soil prop–erties are not very selective. Rather, they are diagnostic of soil taxa with considerable internal variation. Such taxa can be further subdivided by attributing diagnostic value to profile characteristics that reflect processes with a short–er history, such as land use.

Wetland rice cropping is invariably associated with natural or artificial hydromorphic conditions. Rice soils can be placed within an overall genetic context by consider–ing morphometric and analytical soil properties that reflect past soil use for wetland rice cultivation together with inherent, fundamental, profile characteristics. Where flood–ing and rice growing add no new, quantitatively measurable properties to the soil, as in many naturally hydromorphic lowlands, taxonomic classification is based entirely on inherent soil properties (8).

Major soils within each of these elementary landforms will be discussed in terms of their importance for rice–based cropping systems. The soils are characterized using the concepts and terminology of Soil Taxonomy (11). Although such a general inventory cannot possibly be exhaustive, the soil taxa encountered include most rice soils.

Soils of rapidly aggrading coastal plains

Rapidly aggrading coastal plains all are wet and young. Many of their soils are hydromorphic and lack distinct signs of pedogenetic development (Aquents). The youngest soils are close to the shoreline where, in the tropics, tidal flats are colonized by mangroves. They often are Hydraquents, which are grayish or bluish because of their peraquic moisture regime. Upon ripening, either through drainage or following further accretion of the plain, they become more densely packed, with improved trafficability, and develop into Tropaquents or -- where temperature fluctuations exceed 5 K roughly north of the 17th parallel -- into Haplaquents. Rice is of minor importance on the slightly elevated, coarser–textured (former) beach ridges.

Sediments close to the shifting coastline normally are low in pyrite, and potentially acid sulfate soils (Sulfaquents) are relatively rare because the short residence time of the (shifting) mangrove belt allows little organic matter to accumulate. Because organic matter fuels the sulfate-reducing bacteria involved in pyrite formation, rapid coastal accretion generally is incompatible with widespread occurrence of sulfidic soil material (10).

Further inland, soils are increasingly older, and horizon differentiation is more and more conspicuous. Groundwater level normally is shallow, and matrix colors are grayish with a darker surface horizon. Superficial iron mottling reflects water table fluctuations. Such soils are Aquepts, and constitute large areas of recent and semirecent coastal floodplains. Tropaquepts and Haplaquepts are dominant. Development from Aquent to Aquept often takes only a few decades, and the process reportedly is reversible. Where land is too freely drained for Aquept development, aquic subgroups of Tropepts and, at higher latitudes, Ochrepts may be expected. Depending on base status, these soils are Eutropepts/Eutrochrepts (relatively rich) or Dystropepts/Dystrochrepts (poor). On them, rice is planted on bunded, rainfed fields.

Soils in depressions in the inner coastal plains where pedogenetic development is counteracted by peraquic conditions often still are Aquents. Where sediments are older than 5,500 yr, they may have been deposited near a stationary or slowly moving coastline. Those sediments can contain substantial quantities of pyrites (10). In the wide coastal plains of equatorial Southeast Asia, most of these sediments are covered with up to 10 m of ombrogenous forest peat (Tropofibrists). However, they sometimes are exposed. Upon aeration. Sulfaquents rapidly change to very acid Sulfaquepts, which are common on the cultivated deltas of major Asian rivers and also on the west coast of Africa. They are notorious problem soils.

Most coastal rice soils are hydromorphic. Hydromorphic surface soil characteristics are land use-induced only where soils are above the floodplain. This occurs locally in marine terraces or on higher beach ridges but is of limited importance for rice.

Soils of slowly aggrading or stationary coastal plains

Soils of slowly aggrading or stationary coastal plains are similar to those just discussed, but have several differences. For these soils, the greater extent and duration of mangrove occupation and more intense flushing of sediments by tidal creeks often have caused accumulation of substantial quantities of pyrites in sediments near the shoreline (10). The resulting Sulfaquents and Sulfaquepts constrain agriculture, but are nonetheless planted to rice by farming communities that use sophisticated water control and cultivation to keep the pyritic material reduced and nontoxic (3). Elongated depressions filled with brackish mangrove peat and alternating with low (less than 1 m) clayey ridges of saline Halaquepts also occur frequently on stationary or slowly aggrading coastal plains. These unfavorable conditions limit development of ricelands.

Soils in inland valleys

In hilly and mountainous areas, lowland rice is grown on the bottoms and lower slopes of inland valleys. Soils of inland valleys differ widely in parent material and pedogenetic development but have a few similarities in regional variability. Valley bottoms have a longitudinal gradient that is normally steepest near the top of the valley and less at the bottom. The longitudinal slope may be stepped by hard rock-sills. Rice is grown on bunded fields, with field size determined by gradient. Where sediments are added faster than horizon differentiation develops, Aquents and Fluvents are found, but most valley-bottom soils are developed soils and include Aquepts and Aquic subgroups of Tropepts or Ochrepts. Aqualfs, Ustalfs, and Vertisols occur where there is a pronounced, extended dry season. In equatorial regions, the nearly level bottoms of lower inland valleys sometimes are covered with shallow, clayey valley peat (Tropohemists and Troposaprists) that is planted to lowland rice (2).

In many inland valleys, rice cultivation has extended from the bottom to lower hill slopes, and sometimes even steep slopes have been terraced and planted to irrigated rice. Inceptisols dominate the lower slopes, but where soils have remained in situ for a long time, there are pedons with inherited clay redistribution (Alfisols and Ultisols). Man-made Entisols occur on bottomland with irrigation covers (sediment from stagnant, muddy irrigation water) more than 50 cm deep, and also on slopes where terracing has removed the original horizon differentiation.

Many freely drained rice soils show signs of superficial gleying (inverted gley) caused by man-made aquic conditions. Dudal and Moormann (4) coined the term anthraquic to describe this phenomenon. Although an anthraquic moisture regime is not recognized in Soil taxonomy, the term is used in this paper. Anthraquic soils differ from soils with inherent (aquic) wetness in that matrix chromas are higher at some depth than in the superficial gley zone. Downward migration of Fe^{2+} and Mn^{2+} ions from the gleyed surface layer, and subsequent oxide precipitation in aerobic subsurface strata, may occur in rice soils of leveled and bunded fields where groundwater is quite deep. Where iron-enriched subsurface horizons indurate, hard iron pans (padas) can develop that are morphologically comparable to the placic horizons of Soil taxonomy.

Another land use-induced phenomenon common to most puddled ricelands, both with aquic and with anthraquic moisture regimes, is the formation of a dense, shallow cultivation pan. Such pans have no diagnostic significance in soil taxonomy.

Soils of river fans and fan complexes

River fans differ widely in sedimentological and mineral composition and age. Consequently, their soils can belong to a variety of taxonomic orders, ranging from very young Entisols to well-developed Alfisols and Ultisols. There are, however, some clear trends in the regional arrangement of different fan soils. These are mainly due to fundamental differences in soil material and development between the upper and lower sectors of fans.

The intensity of sediment deposition often is greater and sediments coarser near the apex of a fan than in the more gently sloping lower parts. Rejuvenation of fan soils also is more intense and soil horizons less conspicuous in the upper parts of fans and piedmont plains than further downhill. Additionally, water regimes differ. Seepage from higher parts and generally lower hydraulic conductivity in downslope areas often cause marshland to develop where the fan or piedmont plain grades into an adjacent lacustrine or fluvial floodplain. Accordingly, there is a trend toward different land uses. Small, leveled, and bunded seasonal rice fields dominate upper fan areas, and larger, wetter rice fields are common near the base.

A few general statements can be made about the distribution of fan soils, but there are numerous exceptions. Fluvents, Tropepts, and Ochrepts are common in upper fan sectors, often with anthraquic moisture regimes. There may also be soils with structural hydromorphy, including Aquents and Aquepts. Entisols and Inceptisols may occur in lower sectors of young fans, but Aqualfs and Aquults and, slightly more uphill, Udalfs and Udults are more common.

In the lower parts of well-developed fans there are Tropaqualfs and Tropaquults, Ochraqualfs where there are pronounced seasonal temperature fluctuations, and aquic subgroups of Ustalfs and Ustults in drier climates. Albaquults sometimes form in puddled fields on lower fans in the wet tropics. Natraqualfs often occur in seasonally dry climates, where Vertisols also may be found, particularly where the parent material is of basic origin.

Soils of river floodplains

River floodplains comprise three main components: riverbed, levee, and basin. River terraces (not always present) are above the floodplain and are discussed separately. Riverbeds are used for rice in seasonally dry climates, but the total area of such riceland is small.

Levees are not widely used for lowland rice, except adjacent to river basins where rice is grown on levelled, bunded fields. Upstream levee deposits are coarser-textured than those downstream, and become finer with increasing distance from the river bed. Psamments, sandy Tropaquents and, in middle latitude ricelands, Psammaquents occur locally in sandy levee formations. More often, however, levee soils are Fluvaquents, Tropaquepts/Haplaquepts, and Tropepts/Ochrepts with aquic or anthraquic properties. Where levees grade into adjacent basin areas, Aqualfs or Aquults with a shallow cover of more recent levee material sometimes occur. Basin soils are typically fine-textured and hydromorphic, but soil development varies considerably, even within a river basin.

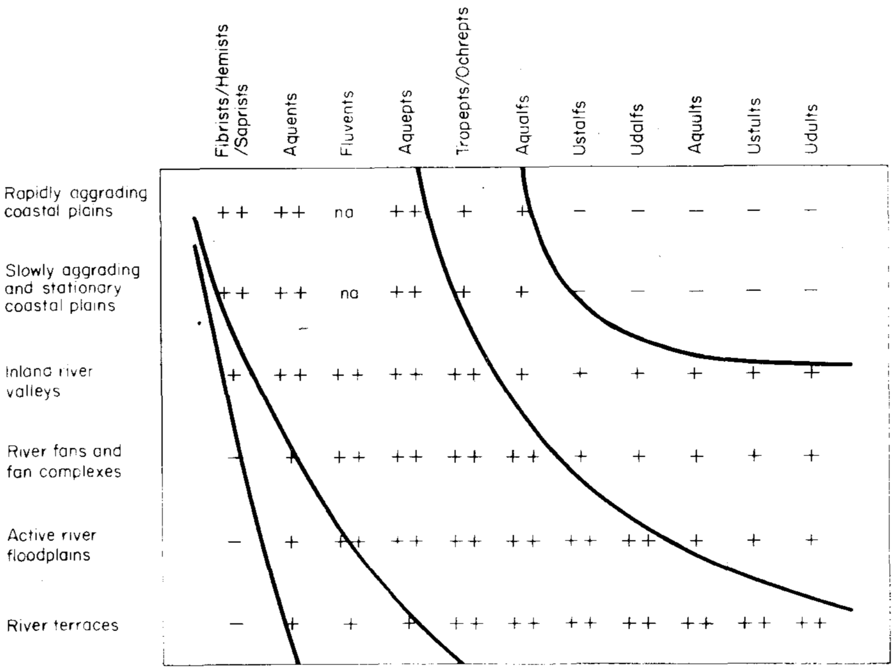
So many different taxa can be found in river basins because of differences in sediment mineralogical composition, rates of sedimentation, the occurrence of remnants of former stream channels, etc. Fluvaquents, Tropaquepts/Haplaquepts, and Tropepts/Ochrepts (aquic subgroups) are dominant in rice areas in young river basins. Where soil formation could advance, Aqualfs and Aquults may be expected. Aquolls occur locally in depressions in richer plains, and Vertisols (Uderts/Usterts) may develop in parts of basins with a lacustrine character where seepage water from adjacent, high base status, uplands enters. Rice fields in depression areas such as filled-in oxbows commonly are peraquic with clayey and occasionally peaty soils. Oxbow soils are poorly developed (Aquents) because they are young, permanently wet sediments.

Terrace soils

Terraces vary in age, mineral composition, height above erosion base level, and topography. Within a given river system, the lowest terraces are the youngest. They have soils similar to those of the adjacent active floodplain. However, terrace soils are not flooded, unless irrigated, and rice depends mostly on rainfall. Tropepts/Ochrepts with anthraquic properties are found on Holocene river terraces, and, in the poorly drained parts, also Tropaqualfs/Ochraqualfs. Older, Pleistocene terraces are higher and have soils that reflect their age and degree of pedogenetic development. Relatively low upper Pleistocene terraces that accompany many rivers, particularly in Southeast Asia, are important rice areas. Their soils are Tropaqualfs and, more often, Tropaquults and Tropudults. Where there are pronounced seasonal rainfall patterns there also are aquic subgroups of Haplustalfs and Haplustults. Rice on terraces often receives supplemental irrigation and soils may show signs of inverted gley, Middle terraces also are widely used for rice. The oldest Pleistocene terraces often are so dissected that the land is undulating and unattractive for rice. Middle and high Pleistocene terraces have soils with advanced profile development including Paleudults, Plinthudults, and Plinthaquults or, in seasonally dry regions, Paleustalfs and Paleustults.

COMMON SOIL SUBORDERS

Figure 1 summarizes the occurrence of the most common soil suborders in the landforms discussed. In addition to those, there are soils and landforms that are of local importance for rice. Some are productive ricelands such as those on



1. Summary of the occurence of the commonest soil suborders in indictaed landforms: na = not applicable, – = absent or rare, + = common, ++ = abundant.

many volcanic slopes. Others are inherently poor, particularly those associated with old, stable surfaces that are not influenced by rejuvenation due to erosion or influx of new soil material.

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PHYSICAL PROPERTIES OF MINERAL SOILS AFFECTING RICE-BASED CROPPING SYSTEMS

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ABSTRACT

To increase cropping intensity, upland crops often are planted after lowland rice. However, lowland rice and upland crops have different soil physical requirements. Puddling to decrease soil permeability is essential for lowland rice culture, but adversely affects upland crops following rice. This article discusses the conflicting requirements of lowland rice and upland crops, changes in soil physical environment caused by puddling as affected by soil physical characteristics, effects of those changes on rice and upland crops, and ways to limit the adverse effects of puddling.

PHYSICAL PROPERTIES OF MINERAL SOILS AFFECTING RICE-BASED CROPPING SYSTEMS

Constantly increasing demands for food require that more be harvested from the same land. Cropping intensity of rice-based systems can be increased by growing more rice crops or by planting upland crops before or after rice. Rice usually is grown in wet season when water is plentiful. Pre- and postmonsoon periods may be relatively dry and favor upland crops. Some rice-based cropping systems are

- rice - rice - fallow,
- rice - cereal (maize, wheat, sorghum, etc.),
- rice - pulse (mung, black gram, green gram, soybean, cowpea, etc.),
- rice - oilseed (mustard, groundnut, etc.).

Because optimum soil physical conditions for lowland rice and upland crops differ substantially, cropping sequences that include both require special management. Moreover, soils react differently to management, depending on soil characteristics. When crops within a sequence have dissimilar soil physical requirements, an understanding of the soil properties influencing the type and magnitude of the soil reactions is imperative to the choice of suitable management practices.

SOIL NEEDS OF RICE AND UPLAND CROPS

Rice is the only cereal that germinates and thrives in water. To retain impounded surface water, soil must have low permeability, whether naturally so or as a product of management. However, in temperate climates, 5-10 mm percolation loss/d seems desirable (15) to leach toxic substances produced when the soil is submerged.

Rice roots have a cortical structure similar to that of many water plants, and lowland rices develop larger root systems in dense, submerged, puddled soils than in upland soils. Because their root system is shallow, seldom extending below 30 cm, lowland rices can grow on shallow, unstructured soils with few large pores.

Upland crops, including upland and wild rices, develop better root systems in dry soils. They need a well aerated seed zone and rooting medium with oxygen in water-free soil pores for root respiration. In well-drained, loamy sand and sandy loam soils without restricting layers, wheat (12), mustard, and barley roots can grow more than 180 cm deep.

Seedbeds must have proper tilth for good seed-soil contact so seeds can absorb water and soil nutrients and for aeration during germination. Upland crops do not grow well on continually submerged soils (2), nor on soils with dense layers at shallow depth. Because water comes to them intermittently, they depend on water stored in the root zone for survival between wettings. Deeper wetting and deeper root systems therefore are desirable.

SOIL MANAGEMENT FOR RICE

Management of rice soils seeks to pond water, and usually includes diking, levelling, and puddling. Diking checks runoff and levelling ensures uniform water level on the field. Puddling is the most important soil management practice. It reduces water losses through percolation, which limits leaching of plant nutrients, and preserves aquatic conditions that favor lowland rice growth (5, 8, 22).

Puddling destroys soil structure, decreases large pores, and increases small pores in the surface layer (8). Increased microporosity and decreased macroporosity lower permeability and increase soil water retention at low tensions. Changing soil porosity also influences the diffusion rate of nutrient ions to plant roots, which may be of major importance for P nutrition. Puddling has been reported to increase rice yield even in soils with less than 10 mm/d permeability.

Puddling markedly increases soil–water retention in soils dominated by 2:1 swelling clays. The effect is less in soils dominated by kaolinite clays (22). Increasing water–holding capacity of rice soils is particularly important because it helps to keep surface soil wet and reduced during brief water shortages. If clay soils dry long enough, the soft mud cracks and dries to a stiff paste. When the soil floods again, the cracks do not completely close and may cause water and nutrient loss through percolation.

For upland crops, tillage provides a seedbed of fine tilth to ensure adequate seed–soilcontact, especially when the seed zone is dry. Sometimes it is necessary to compact the soil with a roller to establish better seed–soilcontact. Deep tillage also breaks up natural or induced restricting layers and stimulates rooting for optimum growth of upland crops.

EFFECTS OF PUDDLING ON SOIL PHYSICAL PROPERTIES

Texture and type of clay mineral, structure, organic matter content, and sesquioxide content determine the effect of puddling on soil physical properties.

Structure

Long-term effects of puddling on soil structure are not well documented. Some scientists report rapid structural regeneration after puddling. Others indicate puddling causes comparatively irreversible changes (27). Generally, puddling causes massive or blocky and platy structure in the upper 10 to 20 cm of the soil (6). Tilth after puddled, flooded rice usually is unfavorable for following crops. Soil breaks into hard, medium-to-large clods, particularly in fine-textured soils. If the soil does not dry, it may be a tough paste after tillage. In contrast to a well-aggregated soil, such a paste is difficult to convert into a soft mud for the next rice season.

The effect of puddling on surface soil structure depends on soil texture and aggregate stability. Aggregate stability is determined by the amount and type of clay fraction; organic matter and hydrous oxides, which may form interparticle bonds; and the electrolyte concentration of the soil solution.

Although puddling usually affects soil structure adversely for upland crops, rice culture sometimes improves subsoil structure. For example, Motomura et al (18) reported that marine clay sediments in Japan developed a prismatic structure with associated vertical fissures during impoldering and ripening. In those soils, puddling increased subsoil permeability.

Stratification

Stratification after puddling is common, especially in medium-textured soils. The sand fraction settles first from the muddy water and gradually is covered by finer silt and clay. The thickness of the layers depends on the original texture. In sandy soils, the clay cover, if any, is thin. In fine clay soils, there may be no coarse layer. In medium-textured mineral soils, as in northern Thailand, stratification is well developed, with a fine-textured surface layer a few mm thick that overlies 1-2cm of almost pure sand (17).

Developing a traffic pan

Moisture conditions during tillage and puddling probably are optimal for destroying the structure of and compacting the soil just under the soft puddled layer. Animal and human traffic add to the compaction. If not loosened, a dense layer of reduced permeability may develop over several years at 10–25 cm depth, and the soil's characteristics of water transmission, retention, and recharge will change (17, 23).

A traffic pan is important to preserve surface water in rainfed and irrigated rice on permeable soils without a natural or induced high groundwater table. It is especially important if the puddled surface layer dries and cracks or where the puddled topsoil is coarse-textured or has high aggregate stability.

Traffic pan development and soil compaction depend on soil texture, structure, and swelling and shrinkage characteristics. Fine loamy soils favor compaction (16). Hydromorphic soils or soils with high clay and sodium contents do not.

Curfs (4) found that in fine loamy sands in Ibadan, Nigeria, incipient pans formed in 3 yr of mechanical lowland rice cultivation. In polder lands with fine, clay sediment, in Shiroishi, Kyushu, Japan, no pans formed during 10–12 yr of rice culture. Incipient pans formed after 50 yr and well-developed pans after more than 200 yr (13, 18). Cracking and self-mulching break up incipient pans in Vertisols. Pans also form slowly in soils with stable structures such as Andepts, Oxisols, and highly organic soils.

Traffic pans help make lowland fields accessible to man, animal, and machine. If the traffic pan is removed from some intermediate-textured soils, the soil becomes deep, soft, and muddy, which limits tractor use. Breaking the traffic pan by deep, mechanized plowing of dry land in northeast Thailand caused serious tillage problems in the following wet season (17).

Repeated puddling where continuously high groundwater prevents drying of the subsoil, or where there is continuous year-round irrigation and poor drainage, can make the soil so soft that it is difficult to cultivate. In Japan, poorly drained rice soils have low bulk densities (<0.9 t/m^3) (24). Drying them for a year or creating a compact layer by using a roller at appropriate moisture content to pack the soil facilitates traffic.

Permeability

Traffic pans in puddled soils have been reported to have very low hydraulic conductivity (7). Moreover, it may be the puddled layer, not the traffic pan, that reduces permeability. The magnitude of the decline in permeability depends on soil texture and structure, clay mineralogy, organic matter content, etc.

Our experience with sandy loam and loamy sand soils indicates that puddling drastically reduces surface permeability and that lowland conditions can be maintained easily after a few years of rice cultivation. In moderately permeable, freely drained soils planted to lowland rice, percolation diminished to 20% of the initial rate in 4 yr, stabilizing at about 12 mm/d (19). In more permeable soils, it took 6 yr of rice cultivation to reach an equilibrium rate of 20 mm/d. In a sandy loam in northern India, 1 yr after puddling, percolation had declined to 20 mm/d (21). More intense puddling of laboratory columns reduced hydraulic conductivity of a loamy sand from 340 to 7 mm/d (20).

Low permeability saves water and reduces nutrient losses by leaching. Soil compaction also reduces percolation rates (8, 20) and saves water, as does lowering the depth of standingwater.

Because puddled soil cracks when it dries, thus accelerating percolation losses, drying should be avoided during rice growth, unless specifically needed to improve subsoil drainage when water supply is plentiful. Tsutsui (27) reported that rice land converted to upland crops and then back to rice needed several years to recover low percolation rates. Puddling without soil submergence restricted root development and decreased rice yield after irreversible shrinkage.

EFFECT OF PUDDLING ON CROP GROWTH

Although puddling favors rice growth, it adversely affects growth of upland crops following rice because it changes seedbed tilth and modified soil–water and soil–plant relations.

Tilth

Plowing soils previously puddled for rice breaks soil into hard, medium-to–large clods that provide poor seedbed tilth and seed–soil contact for upland crops. Large clods permit greater water loss from the surface layers and may cause seed–zone moisture to fall below the level needed for seed germination. Under such conditions, it may be impossible to grow an upland, rainfed crop after rice.

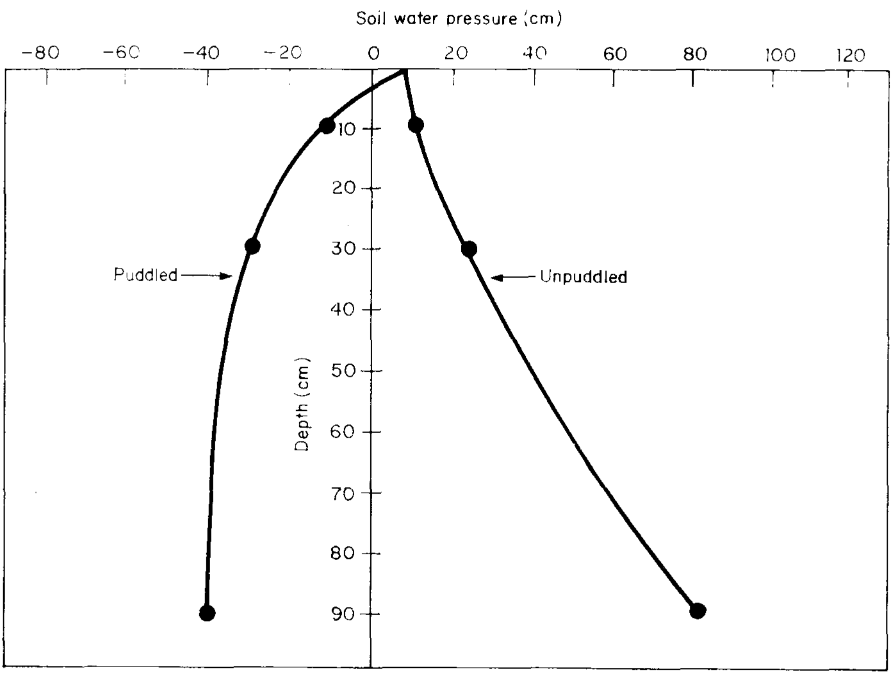
Proper soil moisture and tillage are necessary to achieve a desired tilth. Fine–textured soils, especially those with 2:l expanding clay minerals, are much more difficult to restructure after puddling than coarse soils. Moreover, turnaround time between rice harvest and upland–crop seed–planting may be long if the puddled soil is slow to dry to a cultivable wetness. Such delay may be disadvantageous for the cropping sequence and its productivity.

In loamy sand and sandy loam soils in Ludhiana, India, conventional tillage after puddling produced the same plant population of wheat following rice as that following maize. In Hyderabad, tillage after rice harvest restored aggregate size distribution to its prepuddled condition in coarse-textured, but not in fine-textured soil.

Soil–water relations

The least permeable layer in a soil profile controls water intake and water recharge in the root zone. Below the slowly permeable layer the flow is unsaturated. Sur et al (23) observed that during water infiltration in contiguous puddled and unpuddled sandy loam plots, pore water pressure in subsurface layers was negative in puddled and positive in unpuddled plots (Fig. 1).

Similarly, the shallow, low permeability, high bulk density layer that develops after repeated puddlings changes



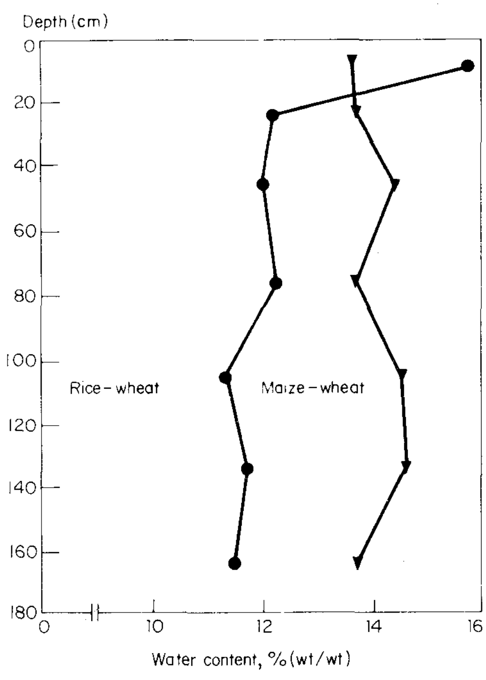
1. Soil water pressure in puddled (planted to rice) and unpuddled (bare) soil at constant infiltration rate.

a profile's water transmission characteristics. After 6 yr of sequential cropping in a sandy loam soil, a maize – wheat profile was better charged than the rice – wheat profile (Fig. 2), and there was a consequent increase in wheat yield (14).

Puddling also changes soil moisture retention and release characteristics. At low tensions, puddled soil retains more water than unpuddled soil and remains wetter longer. This may have a favorable or unfavorable effect on crops. With heavy rain or irrigation, puddled soil has poor aeration longer than unpuddled soil. But during early – season drought, higher surface soil water content may sustain young seedlings longer. Figure 3 shows the effect of puddling on water retention and crop growth in rice – wheat and maize – wheat rotations (23). Early in the season, wheat following rice grew faster than that following maize because surface soil remained wetter in the rice – wheat plot. As the season advanced, wheat following maize grew faster because of the better subsoil moisture regime. The compact layer at shallow depth in rice – wheat plots retarded water recharge and affected soil – plant relations.

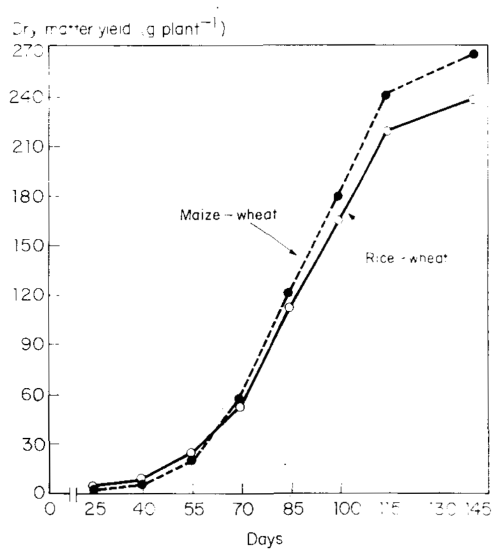
Soil–plant relations

Root system development is adversely affected by dense soil layers at shallow depth. Water absorption and root growth



2. Soi1 water profiles after 24 h of redistribution following infiltration in rice - wheat and maize -wheat plots after wheat harvest.

3. Dry matter production of wheat in rice - wheat and maize - wheat rotations on a sandy loam sold.



are restricted when soil is even mildly compacted. Root elongation rate is inversely related to soil strength (25, 26). Consequently, root development is retarded by traffic pans. Figure 4 shows that after 40 d growth, wheat following rice developed roots more slowly than wheat following maize.

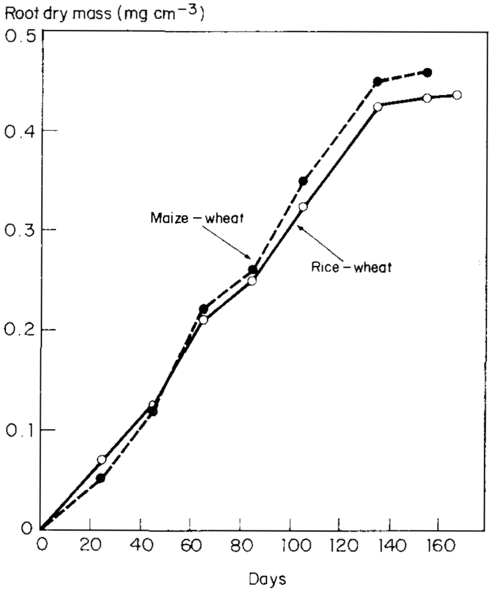
REDUCING THE EFFECT OF PUDDLING

To successfully grow upland crops after rice, it usually is necessary to restructure the soil. Soil texture and organic matter content determine if that can be done.

Texture

Medium – to slightly fine – textured soils favor upland crops because they till well, have high water – holding capacity, good drainage, and good nutrient supplying capacity. Similar or slightly heavier soils such as fine loam, fine silt, and fine clay soils favor rice growth. Soils with 25 – 50% clay in the topsoil and a similar or somewhat higher clay percentage in the subsoil produce the highest rice yields (9).

Coarse – textured soils do not favor rice because they have high percolation rates, poor water economy, and high soluble nutrient losses. They also are not well suited to upland crops because of low cation exchange capacity, nutrient content, and water – holding capacity. However, the negative effects of coarse surface texture diminish with



4. Wheat root growth in a sandy loam soil in rice - wheat and maize - wheat rotations (roots in 1 cm^2 × 60-cm-deep soil sample).

finer subsoil. Therefore, Clarke (3) suggested using a textural value for the complete soil profile rather than surface texture alone to classify rice soils. Harwood (11) developed a texture–based soil classification system that defines multiple cropping potentials of puddled rice soils (Table1).

Organic matter

In addition to supplying nutrients, organic matter promotes soil aggregation. Under submergence, however, it helps create a reduced zone that may favor rice growth, and generally increases water holding capacity of mineral soils. Moormann and Van Breemen (17) reported that high organic matter content reduced drought stress on sandy or coarse loam pluvial rice lands with dominantly kaolinitic clays.

Fine–textured soils, especially those with montmor–illonitic clay, break into large, hard clods that make a poor seedbed for upland crops after rice. Moreover, the high bulk density of such soils affects subsequent growth and yield of the upland crops. Organic matter content is espe–cially important in such soils.

Restoring good tilth after a lowland rice crop is more difficult in soils low in organic carbon (<0.6%) than in humic soils with similar texture and clay mineralogy (17).

Table 1. Soil classification categories that indicate multiple cropping potential in puddled soils with limited and adequate water (11).

		Soil texture			
	2:1 clay	Sandy loam	Silt loam	Clay loam	Clay
	1:1 clay	Silt loam	Clay loam	Clay	
		Percentage increase in bulk density by puddling			
		<4	4-8	8-12	>12
Crop	Water supply	Crop potential after rice			
Peanut	Limited	Good	Intermediate	Poor	Poor
	Adequate	Good	Good	Intermediate	Poor
Maize	Limited	Good	Intermediate	Poor	Poor
	Adequate	Good	Good	Intermediate	Poor
Sorghum	Limited	Good	Good	Intermediate	Poor
	Adequate	Good	Good	Good	Intermediate
Soybean	Limited	Good	Good	Good	Intermediate
	Adequate	Good	Good	Good	Good
Mung	Limited	Good	Good	Good	Intermediate
	Adequate	Good	Good	Good	Good
Cowpea	Limited	Good	Good	Good	Good
	Adequate	Good	Good	Good	Good

Very high organic matter content reduces iron oxide, which dissolves and leaches from the topsoil. Toxic levels of H_2S and organic acids also accumulate and reduce rice yields if they are not leached from the root zone.

Tillage

Tillage kills weeds, breaks clods to form a smooth seedbed, and facilitates root growth by loosening surface and subsurface soil. Loosening puddled, fine-textured, swelling soil may require special tillage. Breaking clods manually with iron rods to prepare a seedbed for wheat is common in the hills of northern India. Large tractors with rototillers that pulverize hard soil are becoming available, but they are too expensive for small farmers. Inexpensive, effective tillage equipment to eliminate drudgery and ensure proper seedbed preparation are badly needed.

Deep tillage has generally been advocated to break up high bulk density root–restricting pans to increase water intake and storage, root growth, and utilization of subsoil water. Considerable research has evaluated the effect of

Table 2. Effect of tillage on yield of wheat after rice in farmer fields in the Punjab.

Soil	Grain yield (t ha^{-1})	
	Conventional	Deep tillage
Silt loam	3.8	4.4
Sandy loam	3.7	4.2
Sandy loam	3.5	4.0
Silt loam	3.4	3.7

deep tillage on crop yields (1, 28), but little has been done to determine the effect of breaking puddling–induced traffic pans on yield of upland crops following rice. Results of some recent experiments (10) with irrigated wheat on sandy and silt loams in the Punjab are in Table 2. Wheat yield increased by 0.3-0.6 t/ha with deep tillage. Similar studies need to be undertaken for rainfed upland crops after rice.

CONCLUSIONS

Rice cultivation in India has spread to soils on which traditionally rice was not grown. Previously, these soils supported two upland crops a year; now, rice is grown in wet season and there has been a congruent decline in yields of the following irrigated upland crop. Some reasons for this decline are known, but further research is needed. Similarly, studies are needed to determine effective and efficient methods for restructuring puddled soils for nonrice crops.

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PHYSICAL PROPERTES OF PEAT SOILS AFFECTING RICE-BASED CROPPING SYSTEMS

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Abstract

Rice-based cropping on peatlands is complicated by the special physical properties of peat soils. Peat-soil matrix geometry differs greatly from that of mineral soil and changes with soil-moisture content, mineral content, and bulk density. Matrix properties are abruptly altered when virgin peats are drained and cropped.

Semiempirical relations are used to explain the loss of peat mass and volume that occurs after a one-time lowering of the groundwater level. The low bearing capacity and trafficability of peats and the relations between their matrix composition, soil-moisture content, and thermal properties also are discussed.

Because of the peculiar moisture regimes and mechanical characteristics of peat soils, each rice-based cropping system has its specific management requirements. These requirements intensify with increased mechanization and cultivation. Matching peat characteristics and cropping system requirements suggests that traditional rice monocropping on shallow or clayey peat soils is the optimum land use for peat conservation. Growing upland crops accelerates land subsidence and peat loss. The potential for intensive, mechanized, rice-based cropping on peat soils is limited.

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Tropical peatlands cover an estimated 32 million ha, less than 10% of the world peat area. Most tropical peats formed in lowlands, mainly in Southeast Asia where 18 million ha of coastal swamps are covered with deep oligotrophic forest peat.

Although rice is by nature a swamp grass, it can be grown successfully in only a small part of the tropical peatlands. Deep oligotrophic peats invariably are associated with sterility in lowland rice, which eliminates about 80% of tropical peatlands as potential rice growing areas.

The reasons for the frequent failure of rice on deep peat soils are not entirely clear, but there are strong indications of soil chemical constraints (4). Where rice will grow on peat, soils have low chemical fertility and there is a variety of soil physical constraints. Nevertheless, there is continuing interest in rice-based cropping on commonly idle peatlands.

PEAT SOIL CHARACTERISTICS

Lowland rice usually is the major crop in rice-based cropping systems, but selection and cultivation of other crops in the system may vary substantially. In this paper, rice-based cropping systems are:

- monocropped lowland rice (single),
- lowland rice sequentially alternating with upland crops (compound), or
- lowland rice interspersed with upland crops (multiple).

Each system has special soil requirements based on the needs of all crops planted. Compound and multiple systems include upland crops that do not grow well on virgin, waterlogged peats. Rice monocropping also requires periodic lowering of the water table. Therefore, forced drainage of peats is a first reclamation measure.

System requirements increase when traditional cropping is replaced by advanced cultivation methods. Irrigation and drainage facilities and. heavy machinery require stable, coherent soils. For sustained productivity, the total requirement of a cropping system must be met by the land characteristics. System requirements can be regarded as static, but peat characteristics change. We discuss physical characteristics that decisively influence the suitability of peatlands for sustained rice-based cropping.

Matrix geometry

Natural peat, like other soils, is a three-phase system. An aliquot of peat, volume V_t, can be divided into solid, liquid, and gaseous components:

$$V_t = V_s + V_1 + V_g \qquad (1)$$

Its dry mass W_d is obtained by multiplying the total sample volume by the bulk density (ρ) of the peat. ρ is the dry mass of unit volume of undisturbed soil. Dry sample mass also can be expressed as the product of solid matter volume and solid matter density (ρ_s):

$$W_d = V_t \times \rho = V_s \times \rho_s \qquad (2)$$

ρ_s of a soil depends on its composition. Pure peat (peat without mineral admixtures) has a typical ρ_s of 1.43 t/m^3. Mineral soil material is more dense. A common value is 2.66 t/m^3. ρ_s of any peat material can be approximated using:

$$\rho_s = [\{(1 - ASH)/1.43\} + \{ASH/2.66\}]^{-1}$$

$$= 1/(0.7 - 0.32\ ASH) \qquad (3)$$

where ASH is the fraction by mass (weight) of mineral admixtures. Combining Eqs. 1, 2, and 3, it is possible to approximate the total porosity of peat materials as a function of ρ_s and ASH:

$$\varepsilon = 1 - \rho/\rho_s = 1 - \rho\,(0.7 - 0.32\ ASH) \qquad (4)$$

where ε is the total porosity.

The ratio $\rho:\rho_s$ equals $V_s:V_t$, the volume fraction occupied by solid matter. It is called the density of arrangement and is an important indicator of the physical quality of peat. ρ and ρ_s can be determined using the same sample.

r is obtained by drying and weighing a known volume of undisturbed peat. If unit mass of the dry peat is burnt to ash, and the ash weighed, r_s can be approximated with Eq. 3.

For virgin peat, r normally is between 0.05 and 0.25 t/m^3. Reclaimed peats are slightly more dense, with r between 0.1 and 0.4 t/m^3.

r increases with mineral content or with decreasing average particle size. The latter is largely a function of the botanical composition and the degree of biochemical decomposition of the peat. Particle size is measured by the content of recognizable peat fibers. e is highest in poorly decomposed *fibric* peats and may exceed 0.95. It is lower, but still over 0.8, in most well-decomposed *sapric* peats. Similarly, pore size distribution varies with ash content and degree of decomposition.

Fibric peats have many wide pores, and correspondingly high saturated hydraulic conductivity K_s that typically exceeds 1.6 m/d, and may exceed 30 m/d. Well-decomposed sapric peat has finer pores and lower K_s. However, these generalizations are not always true. Woody peats nearly always are very permeable to water. Compacted peats have low e and may be virtually impermeable (stratified peats), irrespective of their fiber content.

Subsidence after drainage

Peatland subsides after drainage because of a loss of volume (consolidation) and matter. Subsidence deforms canals, roads, and buildings, causes uneven land surface, interferes with water control, and causes top-heavy crops to lean and trees to fall.

Loss of volume is the main short-term cause of subsidence of reclaimed peatland. Reports from Indonesia indicate surface elevation losses as high as 100 cm during the first year of draining.

Consolidation results from settling after the buoyancy force of the groundwater is removed, and from structural shrinkage caused by increased capillary force on the fiber walls. Consolidation often is divided into primary and secular phases. The primary, *hydrodynamic*, phase is largely a function of the rate of water escape from and through the peat mass. Primary consolidation is initially high because of the generally high permeability of raw peat, but becomes more nearly constant, at a lower value, as permeability decreases with consolidation. Secular consolidation continues long after the hydrodynamic phase has become unimportant. It is more gradual, and may eventually account for half the total loss in volume.

Because of the complexity of the settlement process, its effect on land subsidence is described by empirical relations. The most widely used are the relations suggested by Ostromecki (Eq. 5a) and Hallakorpi-Segeberg (Eq. 5b). Both predict the ultimate loss in surface elevation due to settling S_s after a one-time lowering of the water table

$$S_s = A(Hh^2)^{1/3} \tag{5a}$$

$$S_s = a[(0.08\ Hh/q) + r] \tag{5b}$$

where S_s is in metres, H is total peat depth (m), h is draining depth after subsidence (m), q and r are constants: q = 1.2 m, r = 0.066 m, and a, A are empirical factors with $a \cong 5.5$ A. Values for the empirical factor a were published by Segeberg (9) and suggest that a can be approximated with sufficient accuracy using

$$a = (\rho_s - \rho)/y\rho^2 \tag{6}$$

where the experimental factor $y \approx 80\ m^3/t$. Soil shrinks only above the phreatic level, and shrinkage depends on draining depth and peat properties. A useful analytical or empirical relation to approximately quantify shrinkage has not been identified. Schothorst (7) studied records of 50 yr of subsidence in a Dutch polder and concluded that the loss in surface elevation due to shrinkage was 1.7 times higher than that caused by settling. In another study (8), he reported that during 5 yr, elevation loss to shrinkage was 2.2 times higher than loss to settling.

Subsidence through loss of matter accelerates when peats are drained. Normally, peat loss is caused largely by biochemical disintegration of organic matter (mineralization). Controlled burning, often used in low-input agriculture to improve the chemical fertility of the remaining surface soil, is forced mineralization and will not be discussed in this paper. Peat losses to wind and water erosion are promoted by reclamation but are rarely serious in tropical peatlands.

Peats usually form when near-permanent waterlogging inhibits decomposition of plant debris. The constraint to decomposition is abruptly removed by artificial drainage, which always is followed by increased microbiological oxidation of organic matter. Mineralization rate depends, among other factors, on soil temperature, moisture, pH, and overall nutrient status. Stephens and Stewart (10) approximated the rate of biochemical mineralization as a function of average soil temperature and drain depth:

$$S_m = (-0.001035 + 0.0169h) \times 2^{(T-T_o)/10} \qquad (7)$$

where S_m is subsidence rate due to mineralization (m/yr), h is drain depth (m), T is mean annual soil temperature (°C), and T_o is the threshold temperature for microbial activity (°C).

T_o commonly is 5°C. With 0.9 m drain depth, the estimated subsidence due to mineralization during 1 yr after drainage would be 0.018 m for peat in a cold climate with T = 8°C, and 0.08 m in a tropical region with T = 30°C. Because Eq. 7 is semiempirical, it has limited validity. Its constants were obtained in a Florida experiment where peats had less than 15% mineral matter and r was 0.22 t/m^3. In peat soils with higher r and mineral content, expected subsidence would be 50 to 75% of that predicted by Eq. 7.

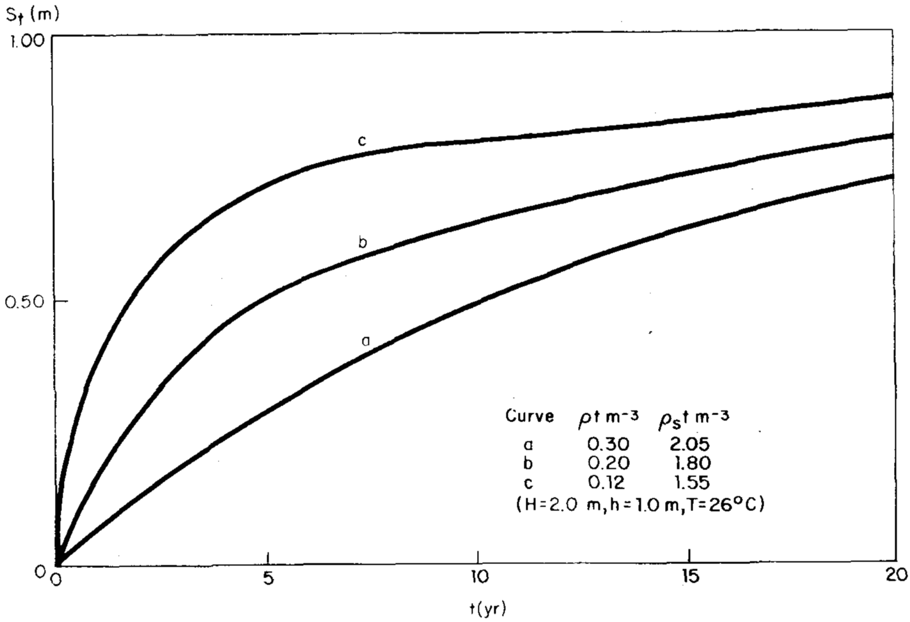
Subsidence after drainage or reclamation is the sum of the partial effects of settling, shrinkage, and mineralization. Murashko (6) described total subsidence over time as a function of peat and water table depths:

$$S_t = aH(1 - \exp\{-h(0.07 + 0.06t)\}) \qquad (8)$$

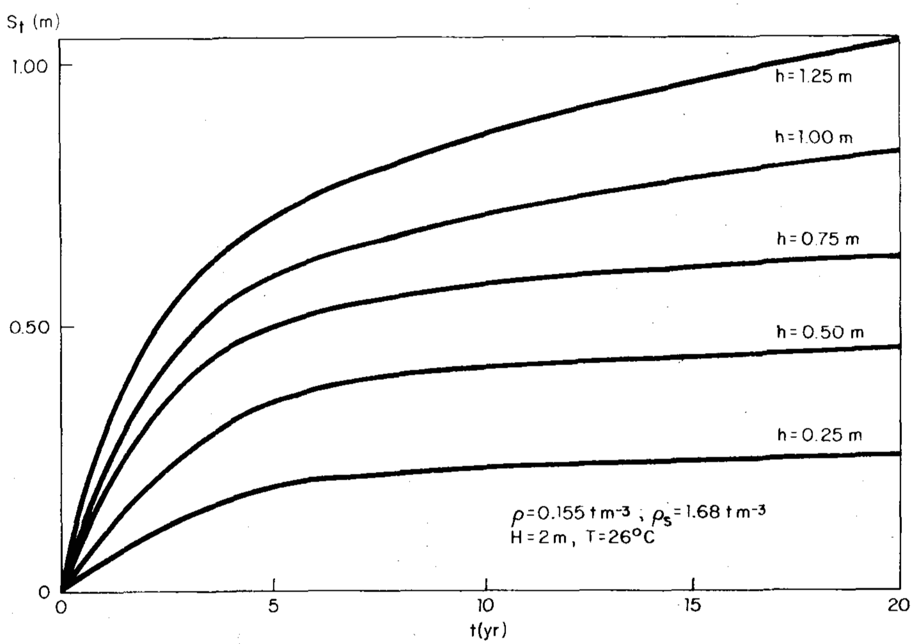
where S_t is total subsidence (m) during a drainage period of t yr, a is a density factor (equal to that in Eq.5b), H the peat depth (m),and h the drain depth (m). Eq. 8 also is semiempirical. It was calibrated with data from Byelorussia, USSR, and is not readily applicable to tropical peat areas.

However, because settling and shrinkage are independent of climate, subtracting expected mineralization under Byelorussian conditions (calculated via Eq. 7) from estimated overall subsidence (via Eq. 8) will predict partial subsidence due to consolidation as a function of peat and water table depths. Total subsidence under tropical conditions can then be approximated by adding tropical mineralization losses to the climate-independent consolidation estimate.

Figures 1 and 2 show the computed total subsidence of an imaginary tropical peat formation (H = 2.0 m; T = 26°C)



1. Computed total subsidence of tropical peat in relation to bulk and particle densities.



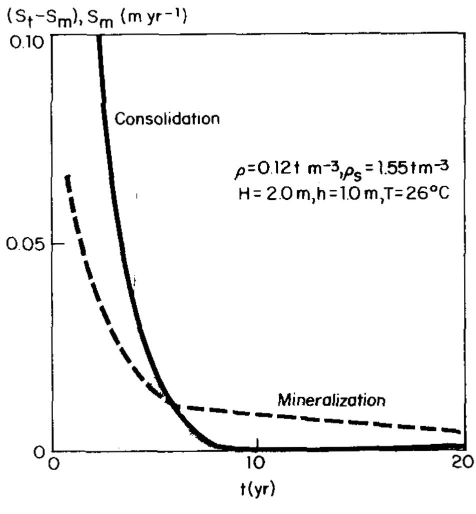
2. Computed total subsidence of tropical peat in relation to initial draining depth.

over 20 yr of drainage in relation to soil density and initial draining depth. The figures show that initial subsidence rates are high because of high (primary) consolidation. Later (secular) subsidence is almost steady and largely dictated by mineralization. Figure 3 shows concurrent consolidation and mineralization rates calculated for an arbitrary situation. Figure 4 shows computed mineralization and consolidation losses over 20 yr for peats with different ρ and ρ_s. The figure suggests that, with the defined system parameters, consolidation stops when $\rho / \rho_s = 0.15$, after which subsidence is from mineralization. Draining depth decreases slowly under these circumstances and mineralization rate becomes nearly constant. This well-known trend in reclaimed peatlands also is apparent in Figure 1, where the slope of curve a is almost constant over time. If ρ is low (curve c, Fig. 1), consolidation losses are initially high, and near-constant subsidence rate occurs only after several years.

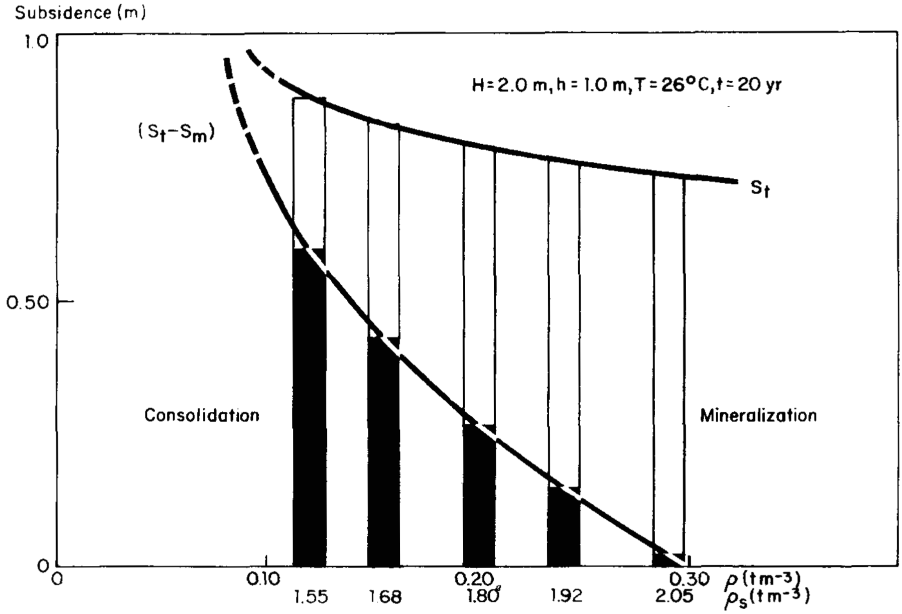
Bearing capacity and shear strength

Bearing capacity and shear strength are important characteristics of peatland. They respectively indicate trafficability and ease of tillage.

Bearing capacity of peats is relatively low. Standard penetrometer readings are between 0 and 40 kPa, compared to



3. Computed partial subsidence rates (consolidation and mineralization) for tropical peat.



4. Computed loss of surface elevation and partial effects of consolidation and mineralization for tropical peats of different bulk and particle densities.

10, 100, or even 1000 kPa for mineral soils. Low penetration resistance makes it difficult to use farm machinery. The ground pressure of modern machinery often is 50 kPa, and even much lighter equipment may get stuck because of high rolling resistance and slip.

Bearing capacity is a function of soil moisture potential, internal friction, and effective normal stress -- stress transmitted through the peat skeleton. Effective normal stress is influenced by r; bearing capacity therefore depends on peat decomposition and ash content.

Shear strength normally is very low in wood-free peats. Standard vane test readings vary between 5 and 20 kPa. Peaty clay values are between 50 and 120 kPa. Shear strength is a function of r, fiber and matrix strength, and water content. Penetration resistance and shear strength increase with compaction, addition of sand, or drainage.

Thermal properties

Thermal inertia and thermal diffusivity determine heat storage and heat and temperature transmission in bulk soil. Thermal inertia is defined as $\sqrt{\lambda C}$, and diffusivity as λ/C, where λ is thermal conductivity and C is volumetric specific heat capacity.

C is determined by soil composition and the volumetric specific heat capacities of the components:

$$V_tC = V_sC_s + V_1C_1 + V_gC_g \tag{9}$$

where C_s, C_1, and C_g are the volumetric specific heat capacities of soil solids, soil liquid, and soil air. De Vries (3) suggested the following values for C for the soil components: organic matter 2.6 MJ m^{-3} K^{-1}, mineral matter 2.0 MJ m^{-3} K^{-1}, water 4.2 MJ $m^{-3}K^{-1}$, and air 1.3 kJ $m^{-3}K^{-1}$.

From Eq. 9, a pure (virtually ash-free) peat with e of 0.93 and 0.64 volumetric water content has C =2.9 MJ m^{-3} K^{-1}. The same peat, water-saturated, would have C =4.1 MJ m^{-3} K^{-1}. Drained peats have lower heat capacity than saturated peats and warm faster. Incorporating sand lowers the heat capacity of peat soils.

Thermal conductivity l of a peat soil depends on composition, ρ, and water content. ρ varies from 0.04 W m^{-1} K^{-1} for fairly dry peats with low ρ and mineral content to more than 0.5 $Wm^{-1}K^{-1}$ for saturated, densely packed peats.

Thermal inertia is much lower in dry than in wet peat. Consequently, diurnal and seasonal temperature fluctuations are more pronounced in reclaimed than in waterlogged virgin peat soils. Low thermal inertia and diffusivity of drained peats also account for the rapid rise in peat surface temperature under direct solar irradiance. In the tropics, high (70°C) temperatures in the top few cm of the soil may cause colloidal transformation of organic compounds and change peat structures irreversibly to desiccated hydrophobic granules and dust. Incorporating sand in drained peats increases thermal conductivity and preserves them (5).

SOIL PHYSICAL CONSTRAINTS TO RICE-BASED CROPPING

As indicated, peats are physically unstable and differ greatly from mineral soils. Moisture regime directly influences their subsidence rate, pore geometry, bearing capacity, and thermal properties. Possible rice-based cropping systems for peatland need specific moisture regimes:

- rice monocropping needs near-permanent waterlogging;
- compound rice-based cropping systems (in which rainfed lowland rice alternates with upland crops on each specific farm, but neighboring farms may concurrently have rice and upland crops) need substantial periods of deep drainage;
- multiple rice-based cropping systems (in which a few elevated ridges with upland crops are cultivated between the preponderant lowland rice fields) need considerable differences in water regime over short distances.

Cropping system requirements increase with the level of applied technology. Traditional agriculture uses simple permanent structures, lightweight equipment, and crop varieties with proven suitability under suboptimal conditions. When agriculture advances, land stress increases because of deeper drainage, more rigorous land preparation, the use of heavier structures and equipment, shorter crop cycles, etc.

Most cropped peatlands suffer an annual net loss of peat because of a high mineralization rate. This is particularly obvious with intensive land use and deep drainage. Considering the serious management problems of farming peat soils, one might ask whether peat loss ought not to be promoted, e.g. by regular burning or topsoil removal.

This action has been advised (2), and could be rewarding where there is good quality mineral soil at shallow depth. However, many peats that qualify for rice-based cropping are on recent coastal sediments that are wholly or partly pyritic. Those mineral materials would strongly acidify under artificial drainage. In such situations, there is every reason to conserve the peat cover.

Maintaining a permanently high water table is the best way to minimize land subsidence (Fig. 2). Rice thrives under prolonged waterlogging, yields satisfactorily at pH 3.5, and has a shallow, fibrous root system that anchors it even on loosely packed peat. If peatlands must be used for agriculture, rice monocropping is an attractive possibility from a conservation point of view. Practice has shown it can be economic. Farmers in South Kalimantan, Indonesia, produce good yields (up to 3 t/ha) on 60-cm-deep forest peat over pyritic sediments. Cultivation is almost entirely by hand. Traditional long-straw varieties are planted and the straw is left on the field after harvesting, which may compensate for mineralization losses.

Areas with peat soils suitable for cultivation usually are small. They are within lagoonal peat formations, e.g. along the Malaysian east coast, and, more inland, among valley peats (1). They are shallow or clayey or both.

Basin peats, the majority of all tropical peats, normally are deep, oligotrophic, and unsuited to cultivation. Small areas of shallow basin peat may be found along the fringes of deep dome-shaped peat bodies. They often are influenced by groundwater and can be planted to lowland rice. However, if the source of irrigation water is a neighboring elevated rain-dependent peat, then there will be drought and sterility problems in dry years.

The small extent of suitable peat soils and the relative inaccessibility of remote peat swamps are reasons for the traditional character of rice cultivation on peat. Advanced, mechanized rice farming is rare on organic soils. Where it occurs, low trafficability, land subsidence, and peat loss are problems. These are self-correcting, however, as the surface soil becomes more shallow and densely packed.

Compound rice-based cropping on (shallow) peat occurs on a very small scale in settler communities where agriculture is largely subsistence-oriented. It is not a true system, and one wonders why a few rain-dependent rice fields are in an area that is otherwise used for upland crops. Soil physical constraints are serious. Rapid subsidence causes an uneven land surface and protruding trees and stumps make land preparation difficult. Rapid subsidence occurs, not so much as a consequence of rice cultivation, but of upland crop cultivation. Upland crops often are cultivated on these peats for only a few years because natural soil fertility decreases rapidly or because severe acidity develops where underlying pyritic mineral sediments are allowed to oxidize.

Multiple rice-based cropping on peat usually is a combination of monocropped rice fields and elevated ridges planted to fiber crops, tuber crops, and fruit (banana, pineapple). Limited labor availability for the construction of the ridges probably explains why the system is not more widely practiced. The system conserves the peat by maintaining a high groundwater table over most of the area and allows a diversity of crops to be grown. It is found in tidally influenced areas where it might be called an improved traditional system. Farmers rely heavily on hand labor. They use moderate amounts of fertilizer and pesticides, and are changing to modern high-yielding rice varieties introduced by extension officers.

We conclude that rice-based cropping on peat is limited to shallow or clay peats and is characterized by small fields, low physical inputs, and high hand labor inputs.

Under such conditions, land stress is low, peat is conserved, and soil physical constraints remain within acceptable limits.

If mechanized rice farming were practiced on peat, buried logs would have to be removed. Even then, mechanization would be hindered by poor trafficability. Peat bearing capacity could be improved by temporary deep drainage, but drainage is associated with severe subsidence and peat loss. Although that might not be prohibitive where shallow peat is above nonacidic mineral subsoil, deep drainage cannot be recommended where pyritic sediments occur near the surface and water control is less than perfect.

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GEOSTATISTICAL TECHNIQUES AND SPATIAL VARIABILITY OF SOIL PHYSICAL PROPERTIES

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ABSTRACT

Geostatistical techniques can be used to characterize the spatial variability of soil physical properties through structure recognition and optimal interpolation. Data from published soil physical variability studies were examined with respect to structure recognition. Many soil physical properties had high short-range variability, as indicated by large nugget variances. To limit short-range variability, measurement method and sample volume must be carefully chosen.

A study is described in which soil-physical interpretations were made from a soil map and from interpolation of individual borings. Both interpretations were tested with 60 independent test borings. There was no significant difference between the two interpretation maps.

GEOSTATISTICAL TECHNIQUES AND SPATIAL VARIABILITY OF SOIL PHYSICAL PROPERTIES

Soil varies with location, and generally the greater the distance between two soil observations, the greater the differences are likely to be. Over relatively large distances (more than a few hundred metres) soil changes often are associated with landscape patterns. Within shorter distances, soil changes are less easy to predict.

Soil spatial variation may be gradual or abrupt. Within a particular area, variation depends largely on the soil property being studied. Variation of dynamic and well-buffered properties such as groundwater level or moisture potential tends to be more gradual than, for example, textural changes in alluvial deposits.

If variations of soil properties are small, the soil is homogeneous. If variations are large, the soil is heterogeneous and complex. Complexity and its spatial scale of variation are important to the use and behavior of soils. Knowledge of the spatial structure of soil properties also helps predict properties of identical soils occurring elsewhere, as shown on soil maps.

The variability of soil properties may be statistically expressed by averages and standard deviations. A review of soil variability studies following classical procedures is presented by Beckett and Webster (1). This way of describing soil variability, however, neglects the spatial dependency between neighboring observation points.

In the last 10 yr, geostatistical techniques have been developed to describe the spatial dependency between individual observation points. They are based on the theory of regionalized variables developed by Matheron (16). Although the theory is from mining engineering, and was developed to estimate ore reserves, it is used in meteorology, hydrology, and soil science.

It is not my intention to thoroughly review the theoretical background of geostatistical techniques. Only some basic concepts will be presented. My goal is to show how the techniques can be used to describe spatial variation of soil physical properties and for optimal interpolation.

SPATIAL ANALYSIS

Spatial structure or dependency between observation points can be geostatistically described by autocorrelation, semi-variance, and intrinsic random functions (IRF). Some stationarity of data is necessary for application of geostatistical procedures. The most common assumptions for data stationarity are expressed in one of the following criteria.

A. Existence of second order stationarity, which implies that the mean (m) does not depend on the location x (the expected value E[Z(x)] of variable Z at location x equals the mean):

$$E[Z(x)] = m \tag{1}$$

and that the existing covariance (C(h)) is identical for the area being investigated, and depends only on the separation distance h between data points, and not on their location:

$$C(h) = E[Z(x)*Z(x+h)] - m^2 \tag{2}$$

With second order stationarity, an autocorrelation function, discussed later, can be defined. In practice, these assumptions often are too restrictive, and the weaker intrinsic hypothesis may be adopted, as follows.

B. The intrinsic hypothesis implies, as before, that the mean does not depend on location x, but second order stationarity is limited to first order differences:

$$2\gamma(h) = E[\{Z(x)-Z(x+h)\}^2] \tag{3}$$

where $\gamma(h)$ is the semivariance. Semivariance is graphically presented as a semivariogram (for example, Fig. 1).

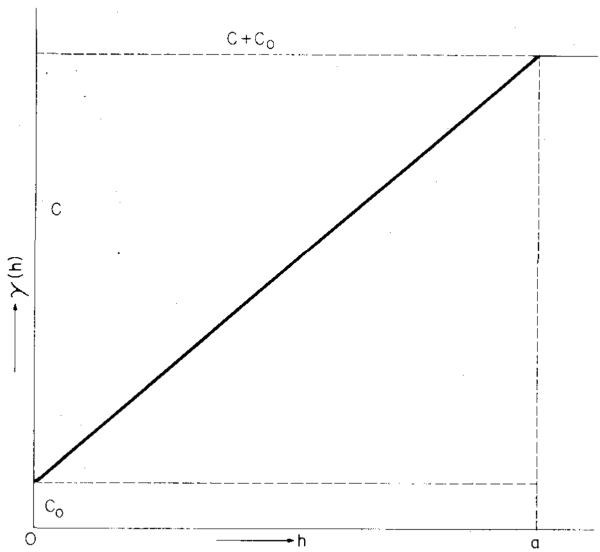
C. Autocorrelation and semivariance cannot be used to describe the spatial relationship between nonstationary data. Nonstationarity occurs when a drift is present in the data, and local average or mean values are a function of the location of data points. In this situation, Matheron (16) and Delfiner (11) describe the data as intrinsic random functions of order 0, 1, or 2 with generalized covariances.

Autocorrelation

The autocorrelation function (r(h)) defines spatial dependency between observation points (see A) and is defined by:

$$r(h) = C(h)/C(0) \tag{4}$$

where C(h) is estimated autocovariance of samples h lags



1. Theoretical semivariogram Indicating the range a, the sill C_0+ C, and the nugget variance C_0.

apart, and C(0) is the estimated variance of the sample set (14). The lag concept, which defines relations between observation points at different distances, is illustrated in Figure 2.

When h = 0, autocovariance reduces to variance, and the autocorrelation has a maximum of 1. At lags greater than 0, autocorrelation tends to decrease with increasing separation or lag. An autocorrelogram is a plot of r(h) as a function of distance or the lag h. In autocorrelation, values are normalized to the range -1 to 1, making them easier to interpret. However, autocorrelation requires relatively strong stationarity.

Several variability studies (9, 12, 20, 23) use autocorrelograms to express spatial variation over distance. Gajem et a1 (12) give a more detailed description of autocorrelograms.

Semivariance

Semivariance g (h) is defined (14) as:

$$\gamma(h) = 1/2\ Var[Z(x)-Z(x+h)] \quad (5)$$

where Z(x) is the value of Z at point x, Z(x+h) is the value of Z at a distance h from point x, and h is the lag.

For second order stationarity, semivariance equals variance minus covariance:

$$g(h) = C(O) - C(h) \qquad (6)$$

where C(O) is variance and C(h) is autocovariance at lag h.

Semivariance is commonly estimated by:

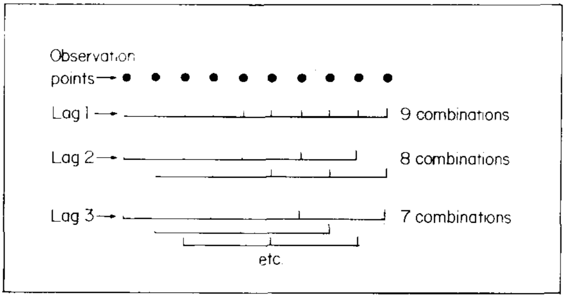
$$\gamma(h) = [1/2(N-h)] \sum_{i=1}^{N-h} [Z(x_i) - Z(x_i+h)]^2 \qquad (7)$$

where N is the number of pairs of data points at a distance h and Z(x) is the value of variable Z at point x.

A graph of γ (h) against h is a semivariogram. Semivariograms reveal the nature of the spatial variation of the property of interest. Figure 1 is a theoretical semivariogram. Semivariance usually increases with distance h up to a maximum. The maximum semivariance is known as the sill: Co+C in Figure 1. The distance a, where the sill is reached, is called the range. Points closer together than the range are spatially dependent. Points farther apart are independent.

Theoretically, γ (O) = O, but a sample semivariogram frequently shows a discontinuity or nonzero value at h = 0. This is the nugget effect and represents measurement error and soil variation within the shortest sampling interval.

Semivariance is an important tool for describing spatial variation in data because it is easy to calculate and demands less stationarity than other methods. It has two main applications: structure recognition and optimal interpolation.



2. Schematic illustration of the lag concept Lag 1 considers differences between adjacent points. Lag 2 considers differences between points separated by 2 intervals. Lag 3 considers 3 intervals, etc.

Intrinsic random functions

With nonstationary conditions, data are split into a drift component m(x) and a residual component Y(x), according to regionalized variable theory (16):

$$Z(x) = m(x) + Y(x) \qquad (8)$$

Drift is a systematic increase or decrease in Z in a particular direction. Drift m(x) at point x is the expected value of Z at x:

$$m(x) = E[Z(x)] \tag{9}$$

The residual Y(x) is characterized by a semivariogram.

According to Matheron (16), nonstationary data can be described by intrinsic random functions of order k (IRF-k). Delfiner (11) found that almost all practical data sets can be described as intrinsic functions of order 0, 1, or 2 with generalized covariances:

$$K(\underline{h}) = c\,\delta(\underline{h}) + a_o|\underline{h}|$$

$$K(\underline{h}) = c\,\delta(\underline{h}) + a_1|\underline{h}| + a_3|\underline{h}|^3$$

$$K(h) = c\,\delta(\underline{h}) + a_1|\underline{h}| + a_3|\underline{h}|^3 + a_5|\underline{h}|^5 \tag{10}$$

respectively, where d (h) is Dirac's delta function. The IRF can be used in the interpolation technique called universal kriging(22).

STRUCTURE RECOGNITION

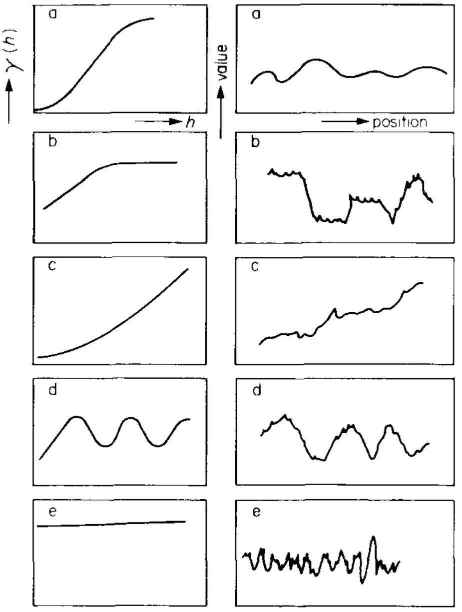
In this section, some properties of semivariograms will be discussed in relation to data structure.

Types of semivariograms

Very smooth variations, such as may be found in groundwater levels, produce parabolic semivariograms (Fig. 3a). Similar semivariograms can be determined for data smoothed by moving averages.

Data with abrupt boundaries at a given distance have linear semivariograms with an abrupt change of slope at the sill (Fig. 3b). If trends are present, semivariograms move upward with an increasing slope (Fig. 3c). If periodic variations are present, they appear (8) as periodic fluctuations in the semivariogram (Fig. 3d). If short-range variations dominate, nugget effect takes up the entire semivariogram (Fig.3e).

More information about semivariogram types in relation to the spatial structure of data is given by Burrough (7) and Huijbregts (13).



3. Theoretical semivariograms (left) and possible data sets they describe (right).

Semivariograms of soil physical data

Semivariograms may be used to identify the homogeneity of the sampling field by studying nugget variances. Nugget variance represents measurement errors and the variation of a soil property within the shortest sampling interval.

If nugget variance comprises the entire semivariogram, the field is homogeneous for the chosen sample size and measurement technique. Nugget variances calculated for some published soil physical data (Table 1) are quite large for certain variables. Because most of the semivariograms were based on reliable data, nugget effects due to measurement errors are a relatively small part of these nugget variances.

For instance, bulk density has a relatively small measurement error, yet Ten Berge et a1 (17, and Table l) reported 100% nugget variance when 100-cm^3 cores were sampled at 4-m spacing. This means that for bulk density a considerable part of nugget variance was caused by short-range variability of the property itself. Other soil properties have similarly high short-range variability (6).

To minimize high short-range variability, attention must be paid to measurement method and, particularly, to sample volume. Some methods yield results directly and do

Table 1. Nugget variances of some published semivariograms of soil physical data.

Property	Reference	Lag (m)	Nugget variance (%)	Max transect (m)	Observations (no.)
Moisture supply capacity	18	50	50	*a*	530
Infiltration rate	20	1	13	*a*	1,280
Bulk density	12	0.20	15	20	100
Available water content	19	10	46	*a*	38
Moisture content at pF 2.5	19	10	23	*a*	38
Saturated hydraulic conductivity					
X-Y-plane	9	0.15	*b*	*a*	200
X-Z-plane	9	0.15	100	*a*	170
Y-Z-plane	9	0.67	100	*a*	170
Moisture tension					
transect 1	17	4	100	200	50
transect 2	17	4	100	200	50
Surface temperature					
transect 1	17	4	6	200	50
transect 2	17	4	16	200	50
Bulk density	17	4	100	200	50

[a]Not measured on a transect. [b]Cannot be calculated from published data.

not require elaborate calculations that may be a consider–able source of variation (2). Other methods may not be suit–able for particular soil types or conditions (3). In such circumstances, their use introduces variability that is not related to soil properties, but simply reflects incorrect procedures.

Additionally, sample volume is very important. Each sample should have a minimum Representative Elementary Vol–ume (REV) that accurately represents the soil horizon to be characterized. A REV may be 100 cm^3 in a homogeneous sand, but 15,000 cm^3 in a clay soil with clearly developed peds (2). There is very high short–range variability when a 100–cm^3 soil core is used to measure physical characteris–tics in such a clay soil. Some cores contain cracks, others don't. In this case, incorrect sample volume will make short–rangevariation very high. A meaningful reflection of spatial variability can only be obtained when samples have a minimum REV, an aspect often ignored in variability studies.

OPTIMAL INTERPOLATION

Theory

There are several methods for spatial interpolation between point data (18, 21). One is kriging. Kriging is based on the theory of regionalized variables, and produces estimates for unmeasured positions that are optimal in that they are unbiased and have minimum variance. Mathematically, these conditions are expressed as:

$$E[\hat{Z}(x)-Z(x)] = 0$$

$$\text{VAR } E[\hat{Z}(x)-Z(x)] \text{ is a minimum} \tag{11}$$

where Z(x) is the observed value and $\hat{Z}(x)$ is the predicted value. An important advantage of kriging over other interpolation methods is that variance of the estimates can be determined. The interpolated values can therefore be used with known confidence.

In kriging, the interpolated value for an unmeasured position is a weighted average of neighboring observations. The values for unmeasured positions can be mathematically estimated by solving the following n+l linear equations:

$$\sum_{j=1}^{N} a_j \gamma(x_i, x_j) + \mu = (x_i, x_o) \qquad (i = 1 \text{ to } N)$$

$$\sum_{j=1}^{N} a_j = 1 \tag{12}$$

where N is the number of values used to estimate the unmeasured value, a_j is the weight of thejth neighboring value, m is a Lagrange multiplier, and g (x_i, x_j) is the semivariance between the ith and jth value.

It is necessary to know the form of the semivariogram to solve the kriging equations (12). The form is estimated by fitting a model semivariogram to the experimental semivariogram (14). Journel and Huijbregts (14) describe several semivariogram models. Fitting the model to the experimental semivariance is the weakest part of the kriging procedure because there is little theory that relates these mathematical models to the physical reality of soil variation.

A semivariogram cannot be used to describe the spatial structure of nonstationary data (refer to section C, page 87). Instead, we can use intrinsic random functions to describe the structure of such data. This more general model is called universal kriging, and can be used where there is drift.

A case study

The following case study is an example of universal kriging. Hydrological interpretations were made from a soil map, and by kriging the individual borings. The resulting interpretation maps are referred to as simulation maps. Both simulation maps were evaluated by comparing their predictions with measurements made by independent borings at the 60 chosen sites.

The study area of 125 ha was part of e 650 ha site that had been the subject of a detailed soil survey to provide soil physical data for a simulation model of water regime in the unsaturated zone. The 125 ha area is underlain by Miocene clay sediments that start between 20 cm and 10 m depth. Glaciers deposited boulder clay in an early Pleistocene period. Later, aeolian sands were deposited over the area, forming a surface relief that is quite different from the underlying boulder clay surface.

The simulation map, derived from the soil map. The soil survey was at 1:5000 scale, with an average observation density of 1.6 borings/ha. The Dutch soil classification system mainly concerns properties of horizons near the soil surface. However, for this survey intended for hydrological interpretations, additional samplings were made in appropriate subsurface horizons. In particular, observations were made of the starting depths of gravel and boulder clay. These, with observations of the thickness of the A horizon, will be used to develop the simulation map.

To demonstrate that the three soil horizons delineated by the pedological classification did indeed differ in soil physical properties, replicated measurements of hydraulic conductivity and moisture retention curves were made (24) for each horizon. Statistical comparison of the curves showed that there were significant differences in soil physical properties.

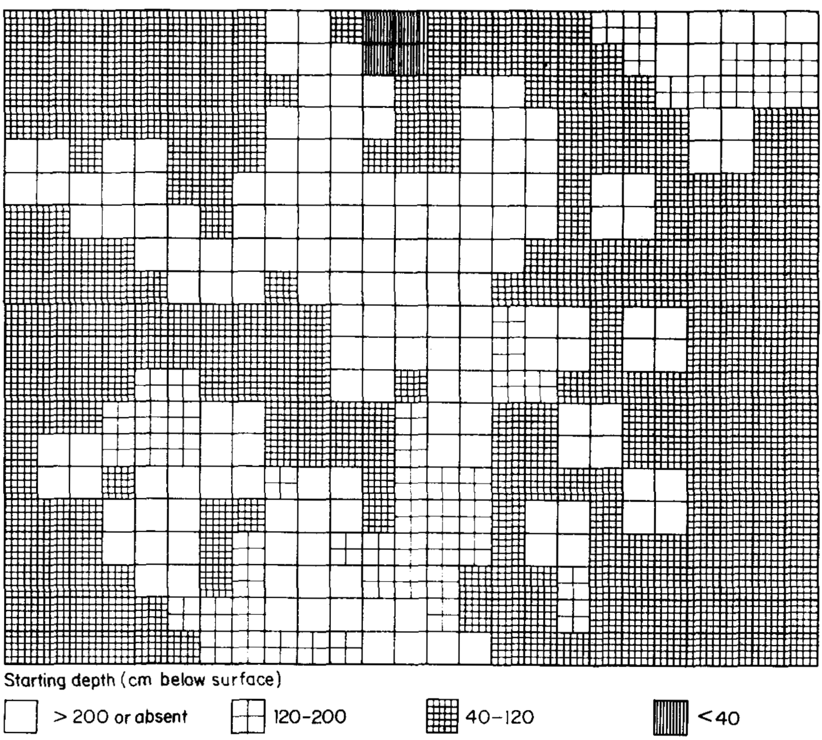
The thickness or starting depth of the horizons were combined and classified and displayed on the simulation map. For any location on the map, a sequence of thickness and depth of physically significantly different major horizons was defined.

The simulation map, derived bv kriging. A kriged simulation map was developed by kriging the soil profile data of the survey borings, using soil horizons that were, as for the soil map simulation, physically significantly different. Detailed results are reported by Bregt and Bouma (4). The data were nonstationary, so IRF instead of semivariance was used to describe spatial structure. After interpolating values for A horizon thickness and for starting depths of gravel and boulder clay, the results were combined and classified in the same way as for the simulation map derived from the soil map.

Kriging of the three thicknesses and depths was through the AKRIP computer program (15). For each property, kriging took four steps.

1. Identifying the order of the intrinsic random function.
2. Determining the coefficients of the generalized covariance models that are appropriate for the already determined order of the intrinsic random function.
3. Selecting the best generalized covariance model.
4. Applying point kriging.

After kriging the single properties the results were visualized by the CELPLOT program (5). The kriged map for the starting depth of boulder clay is given as an example in Figure 4.



4. Kriged map for starting depth of boulder clay (scale 1:10000).

Table 2. Validation of the simulation maps derived from the soil map and by kriging. Assessments of purity are based on data from 60 independent borings.

Property	Purity (%)	
	Simulation map derived from the soil map	Simulation map by kriging
Thickness of A-horizon	80	83
Starting depth of gravel	83	86
Starting depth of boulder clay	68	61
All data	77	77

Validation. The purity of the two maps was tested against 60 independent borings, using statistical procedures described by De Gruijter and Marsman (10). The percentage purity (Table 2) indicates the degree of agreement between the predictions of either simulation map and true values determined through independent borings. Both maps have a purity of 77%. The simulation map, based on the delineated areas of the soil map, does not differ significantly from the kriged simulation map.

In earlier studies, van Kuilenburg et al (18) also found no significant difference between the purity of predictions for soil moisture availability derived from a soil map or from kriging. More investigations are needed to compare the merits of these techniques for characterizing soil spatial variability.

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PHYSICAL MEASUREMENTS IN LOWLAND SOILS TECHNIQUES AND STANDARDIZATIONS

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ABSTRACT

The paper reviews methods for making soil physical measurements. Also discussed are methods for sampling and for determining soil consistency, cohesion, shear strength, structure, porosity, and water movement and their applicability for puddled lowland rice soils. Standardization of measurements is considered difficult because methods are not always suited to all soil conditions and because too few data are available from comparative studies of measurement techniques.

PHYSICAL MEASUREMENTS IN LOWLAND SOILS: TECHNIQUES AND STANDARDIZATIONS

The suitability of land for lowland rice is determined primarily by climate, topography, and hydrology. Soil characteristics, such as drainage, permeability, texture, fertility, chemical composition, pH, and salinity, are of secondary importance, although they often determine rice yield potential, and may even preclude lowland rice cultivation.

Furthermore, lowland rice tillage practices tend to alleviate problems caused by adverse soil characteristics. For example after tillage, permeability usually decreases, nutrient availability and organic matter increase, and pH tends toward the optimum. It therefore is not surprising that lowland rice is grown on a wide range of soils. Only coarse sandy soils, deep peats, extremely acid soils, and alkali and saline soils are unsuitable.

Although high yielding varieties and extensive research to improve soil fertility have produced substantial yield increases, little research has focused on the physical characteristics of lowland rice soils. With enough water, current yield targets (4–5 t/ha) in tropical rice producing areas apply more or less regardless of soil physical characteristics (21). However, it is generally accepted that physical characteristics do have some importance: "The surface layers of the soil must have a moderate clay content, a reasonable depth, and a moderate degree of permeability (39)."

The relatively slight importance ascribed to soil physical effects on rice growth contrasts sharply with the profound effects of tillage. Traditionally, lowland tillage consists of flooding and repeatedly plowing and harrowing very wet soil. This reduces soil stability, destroys soil aggregates, partially disperses the clay fraction, and alters pore size distribution.

Wetland tillage creates a soft, noncohesive, nonsticky plow layer with reduced permeability and makes it easy to transplant rice seedlings. Puddling is considered essential to successful rice cultivation. Where there is enough water and power, puddling is almost always practiced on near-impermeable soils with high expanding clay content, and also on nonplastic sandy soils.

It is difficult to quantify the changes in soil structure caused by puddling. Most studies of puddled soils or of effects of puddling on soil and yield have limited value because the degree of puddling usually is inadequately defined. Apart from changes in soil physical properties caused by lowland tillage, soil changes during and after rice cropping need to be considered, especially where dryland crops follow rice.

We discuss measurements of soil physical characteristics and indicate their importance in lowland rice cultivation.

SOIL SAMPLING

A soil sample is a specimen of soil taken to represent a body of soil. Its size and form depend on purpose. Samples for measurements that are sensitive to changes in soil structure, as are most soil physical measurements, should be taken without disturbance. If the properties to be measured are prone to sudden changes, sampling should be under carefully defined conditions. For comparative studies, sampling techniques must be standardized.

Core samples are normally taken for physical measurements, although aggregates or peds sometimes can be used if they are not altered during handling and transport. The best core samples are taken when soil water potential is near the wet limit of the plowing range. For sandy soils, the wet limit is about –5kPa and for clayey soils about –100kPa. At lower soil moisture potentials, soils are either too loose or too hard to be sampled. At higher soil moisture, soils become plastic and deform easily.

There are many core samplers available for dryland soils. When correctly used, they perform well as long as soil moisture content is below the liquid limit. At moisture contents between liquid limit and flocculation limit, a partial vacuum inside the sampling cylinder usually is needed to prevent the soil core from slipping out of the sampler (31).

Undisturbed samples from newly well-puddled, flooded soils are almost impossible to take. The soil particles move freely and the soil acts as a viscous liquid or a gel. Although sampling is unlikely to significantly influence general particle arrangement, it may be difficult to lift a sample from the field without inducing some restructuring by drainage os pressure. Thus, cores of 0.078 x 0.040 m, taken at a 45° angle from a newly puddled Vertisol and closed with flat plastic lids when still immersed, had a bulk density that agreed to within 10% with the value determined by digging soil from an enclosed area in the field. Moreover, reproducibility was good: the coefficient of variation was less than 10%. However, the samples were structurally disturbed by transport and manipulation and they were unfit for physicalmeasurement.

Methods to reproduce the field tillage process in the laboratory must be developed to overcome sampling, transporting, and handling problems. In the laboratory, the soil should be puddled similarly, with equal specific energy input, and to a similar degree as in the field.

SOIL CONSISTENCY, COHESION, AND STRENGTH

Consistency indicates the soil state that results from the apparent internal forces of adhesion and cohesion. Water content is the main determinant of consistency. Typically, soil consistency varies from hard when dry, to friable when moist, plastic when wet, and liquid when saturated. Although transition between states is gradual, Atterberg devised simple tests to determine water content at transition from friable to plastic, plastic limit, and from plastic to liquid, liquid limit. Those tests, and procedures to determine shrinkage limit and sticky point, are described in appropriate handbooks (2).

Although consistency limits can be used to classify soils for workability or puddlability (4), swelling and shrinkage (26), compressibility (36), and permeability (15) and correlate well with clay content and nature (16), they have been little used for characterization and suitability classification of lowland rice soils.

The cohesive forces between particles not only determine soil consistency but also strength. Koenigs (22) extensively discussed the relation between soil cohesion and strength and the puddling of clay soils. Soil strength affects trafficability, machine performance, and root proliferation (20, 34). It is related to soil cohesion and the coefficient of internal friction by the Mohr-Coulomb equation.

There are two widely accepted methods for determining soil shear strength: the direct and triaxial shear tests. Both require accurate equipment and skills normally unavailable in agricultural soils laboratories. For rice soil studies, the simple vane shear test (1) is quick and can be done in the field at any desired depth. The torque necessary to rotate the vane, and thus shear the soil, is directly proportional to soil cohesion.

An indirect but extensively used tool for characterizing soil strength is the penetration of a probe fitted with different tips. There are three groups of penetrometers: those that record the pressure necessary to push the tip a specific distance into the soil (static-tip), those that measure the pressure required to move the tip through soil at a constant rate (moving-tip), and those that record the number of blows required to drive the tip to a specific soil depth (impact) (33). A penetrometer reading is an integrated index of shear strength, compression, metal-to-soil friction, etc. Nevertheless, it is highly correlated with cohesion determined using a vane shear test (34).

The modulus of rupture, a measure of tensile strength of dried soil, is particularly useful in studies on crust formation and seed germination following lowland rice. In the method, a small beam is centrally loaded with a specially prepared soil until the beam ruptures. The modulus of rupture of a crust on a given soil results from complex physical and physicochemical processes and does not correlate with any simple soil characteristic (5).

SOIL STRUCTURE

Soil structure is the arrangement of primary soil particles into clusters. Clusters are discrete from adjoining clusters and have properties different from an equal mass of unaggregated primary particles (35). The arrangement of soil particles in aggregates, and aggregate size and strength and stability, result from the nature of the primary particles, from the forces acting between them, and from the external forces acting on the soil body. The number, shape, and stability of the voids in a soil are a direct consequence of the soil's structure. Soil structure influences many processes in the soil-plant-atmosphere system, such as storage and transport of fluids and heat, water and nutrient uptake, seed germination, and root proliferation.

Soil structure has long been recognized as important to crop growth and production, but objective methods to present soil structure as a single quantitative value have not been developed, although many techniques have been developed for measuring aggregate stability. Usually, measurements are made of one suitable physical or mechanical soil variable that is related to soil structure. The precise nature of the relationship, provided it exists, is difficult to establish.

Methods based on an analysis of the aggregate size distribution of dried soil, and the stability of the aggregates when they are immersed in water, are numerous. Some use the difference in the weight of aggregates of a selected size before and after sieving in water as a measure of aggregate stability. In others, the mean weight diameter of a range of aggregate sizes in the soil is measured before and after sieving in water and the difference is used as an index of (in)stability (37).

Dry and wet sieving cannot determine soil structure in the field because results depend on the procedures followed to store and dry the soil, break it into selected aggregates, select aggregate sizes, wet the aggregates, and sieve the soil. However, if standardized, these methods can be useful for comparing the effects of soil management and cultural practices on aggregation (6, 9, 13).

The structure of puddled soils cannot be evaluated by dry and wet sieving because the procedure involves drying, and thus restructuring the soil, before aggregate distribution and stability can be determined. The method, however, can be used to study the evolution of the structure of puddled soils subject to drying and rewetting (Table 1).

Methods that simulate a destructive force or a combination of destructive forces have been used to study aggregate stability, but their suitability for evaluating puddled soils has not been tested.

The turbidimeter technique (12) could be modified to study the effect of sesquioxides, organic matter, or a combination of both on aggregate stability. Instead of dry aggregates, the whole puddled soil could be subjected to mechanical shaking in a water–glycerol mixture, after which the turbidity of the suspension could be measured.

The air–water permeability ratio method (29) is based on the degree of slaking when soils are saturated. It may indicate the puddlability of soil. The classification of aggregates based on their coherence in water, proposed by Emerson (14), also may be useful.

There is no standardization in measuring methods or reporting of measurements of soil structure. Methods have been continuously modified to suit the particular problem under study. Work is needed to develop techniques in which

Table 1. Effect of drying and rewetting on the structure of a Vertisol and an Ultisol that initially were puddled.

Drying cycle	Vertisol		Ultisol	
	% aggregates < 2 mm	Stability index	% aggregates < 2 mm	Stability index
Upland soil	78	137	71	56
Puddled soil	9	Water stable [a]	52	Water stable [a]
1	78	233	43	28
2	79	196	48	35
3	86	128	20	43
4	82	108	13	–
5	83	115	9	–

[a]Percentage of aggregates was determined by sieving under water.

the nature and magnitude of the forces acting on aggregates or the whole soil can be quantified. The measurement of shear strength at different soil water potentials and the detachment of soil particles under the impact of water drops (11) show promise.

SOIL POROSITY

Soil structure implies the existence of cracks or pores between soil aggregates. The size, spatial distribution, and longevity of those pores that are large enough to be, but are not, filled by other soil particles distinguish a structured from a structureless soil.

Total soil porosity relates directly to bulk density and to soil particle density. Bulk density generally is determined by finding the mass of dried soil of an undisturbed core sample of known volume. Problems in determining bulk density are associated with sampling problems. Bulk density of an individual clod is determined from the mass of the dried clod and from its volume measured by immersion in mercury or in water after coating it with paraffin wax. For cohesive soils, sand-funnel and balloon techniques can be used in the field (2).

In lowland rice soils, where swelling and shrinkage nearly always are encountered, the double-source gamma ray absorption method may be particularly useful when the difficulties in collimation, discrimination, and alignment of the probes are solved. The method permits simultaneous measurement of bulk density and soil water content, but presently is impractical for field use.

Pores in soils have different functions according to their size. They can be classified accordingly (17). Pore size distribution is an important soil characteristic but few data are available because of measurement difficulties. For a rigid pore system, pore size distribution, characterized by the radii of the pores, is usually determined from a water desorption curve. The relation between pore radius and the pressure required to remove water from the pore can be written as:

$$r = -2T \cos \theta / h \rho g \qquad (1)$$

where r is the radius of the pore, T is surface tension of water (0.07 N/m), q is contact angle (0 in most soils), h is water potential in height units, r is water density, and g is the acceleration due to gravity. The difference in volumetric water content of a soil at two different water potentials is equal to the space occupied by pores of which the maximum and minimum equivalent radii correspond to the higher and lower water potential. The required water desorption curves can be determined by a tension plate assembly or sandbox apparatus and by a pressure plate or pressure membrane apparatus. But interpretations are complicated by hysteresis. In one study, Bouma (7) compared results obtained from desorption and absorption curves with results from a morphometric point count technique. He concluded that the desorption curves, which might be expected to relate directly to the actual pore size distribution, did in fact give erroneous results in all the soils tested. Because morphometric techniques are governed by probability, they should yield results intermediate between those of absorption and desorption.

In swelling soils, determining porosity and pore size distribution is much more difficult because both properties are functions of water content. Moreover, in puddled soils, drying irreversibly modifies soil structure (10).

Three ranges of water content can be recognized in swelling soils (27):

- The normal range, where a decrease in water content causes an equal decrease in soil volume. The soil cracks, but the aggregates remain saturated.
- The residual range, where the decrease in water content is not matched by an equal decrease in soil volume. Air enters the soil aggregates and the soil loses plasticity.
- The zero range, where a decrease in water content does not change soil volume. The soil system has become rigid.

Bulk density and moisture content must be measured to determine total porosity in the normal or residual ranges. This can be done with the double source gamma ray absorption technique. Porosity at the lower limit of the residual range can be determined by the absorption of nonpolar liquids, such as benzene or carbon tetrachloride, which do not cause significant swelling.

Lawrence (24) and Greenland (17) reviewed some techniques for determining pore size distribution in swelling soils. Morphometric techniques are best suited to study of pores with an equivalent cylindrical radius larger than 30 μm. In this method, pore sizes and shapes are determined from thin sections of resin-impregnatedsoil using electro-optical image analysis.

To a limited extent, N sorption at −196°C, and mercury intrusion after evacuating water from swollen soils by freeze-drying, have been used to measure pores down to an equivalent cylindrical radius of 5 nm in moist soil (28). These methods show promise but still have many difficulties. Problems have included volume changes resulting from pre-drying the samples, and bulk density increases caused by the pressure needed to inject mercury into the smaller pores. Furthermore, results relate mainly to intra-aggregated porosity, because of the small sample size used in these techniques. However, it is cracks and interaggregate pores that play a dominant role in many physical processes such as water storage, aeration, and infiltration in swelling soils.

WATER MOVEMENT

One of the major reasons for puddling rice soils is to decrease hydraulic conductivity (30). Decreases may be of several orders of magnitude in clay soils, but are less in sandy and montmorillonitic clay soils. Reorientation of soil particles in puddled soils often is anisotropic. Thus in rice fields with horizontal hydraulic gradients, both the horizontal and vertical hydraulic conductivities should be determined.

Rates of water loss through soil (percolation plus seepage), and the influence of soil properties and management practices on them depend not only on soil type. Although they do relate strongly to many soil properties, they depend also on factors related to landscape position, proximity of drainage ways, field management, and groundwater table level.

Laboratory methods for measuring the hydraulic conductivity of saturated soil have been reviewed (2) and permeameters for routine determinations on soil cores are commercially available. However, values obtained with laboratory methods rarely equal field values.

Data from comparative studies (18, 23) indicate that laboratory methods sometimes overestimate hydraulic conductivity by more than an order of magnitude. Preferential percolation along the walls of the sample holder and an increased number of continuous pores and channels in the sample have a significant positive effect on hydraulic conductivity. There are smaller, negative effects of structural changes during sample manipulation, smearing of the sample surface, and enhanced blocking of the pores by microorganisms and their products. Anderson and Bouma (3) observed an exponential decrease in hydraulic conductivity with sample length. Laboratory methods should only be used in comparativestudies.

When reliable absolute values of hydraulic conductivity are needed, field techniques should be used. Commonly used field techniques were discussed by Bouwer (8), but these are difficult to apply in the plow layer of rice soils. With some precautions, the piezometer method can be used to determine vertical and horizontal hydraulic conductivity although it may be difficult to obtain and maintain a cavity in puddled soil. Through Darcy's law, the vertical saturated hydraulic conductivity of the puddled plow layer can be easily obtained from flux and hydraulic potential at two depths. Flux can be measured with an infiltrometer and the potentials with piezometers.

In flooded rice soils where the water table remains below the plow layer, the difference between the hydraulic conductivities of the plow layer and the subsoil frequently causes the subsoil flow to be unsaturated. The steady state downflow of water in a layered soil was analyzed by Takagi (32) and Bouma (7) and others, but field experiments have not been done.

This problem and problems related to water redistribution in the soil after irrigation ceases require knowledge of hydraulic conductivity as a function of matrix potential. The internal drainage method (9) probably is the most widely used. It requires the simultaneous measurement of soil water content and matrix potential by, for example, a neutron moderation moisture meter and tensiometers. Libardi et a1 (25) assumed an exponential relationship between soil water content and hydraulic conductivity. They concluded that simple field methods, which only require a measurement of soil water content profiles, thus allowing more observations at a lower cost, are better than fewer, more exact observations that are less amenable to statistical analysis over large land areas.

STANDARDIZATION

These techniques for physical measurements in soils are only a sample of the techniques that have been developed. Researchers continuously devise new techniques or modify existing methods to obtain data in a form suited to test hypotheses. Hence comparison of results from different sources is difficult. For example, determining aggregate stability depends very much on the size of the aggregates studied because the forces responsible for stability may differ accordingly.

Standardized techniques must be universally applicable but few techniques have been used on different soils and on soils in different conditions. Rigorous studies comparing soil physical measurements are scarce and most studies look for correlations rather than explanations.

Lowland rice soils usually are thought of as puddled soils and their physical characteristics are almost invariably compared to those of corresponding dryland soils using techniques suitable only for dryland soils. In this respect, the puddled state of the soil is considered to be unique, which it most definitely is not.

Presently, standardization of techniques for lowland rice soils is hardly feasible. The possibilities, advantages, and disadvantages of the different techniques should first be fully established.

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HYDROLOGY OF RICELANDS

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Abstract

We relate hydrologic classifications of ricelands to rice cultural types at several scales, e.g. Asia (schematic), a large river basin (1:4 million), a large delta (1:250,000 or 500,000), an intermountain basin (1:100,000 or 250,000) and the riceland of one village (1:l0,000 or 20,000). Physio-graphic and geomorphologic control of hydrologic regimes in ricelands is discussed. A scheme is proposed to inventory Asian rice cultural (land) units on a mesoscale (1:50,000 or 250,000) using LANDSAT imagery and extensive field surveys. Its adaptive approach and its adaptability to the Chiang Mai-Lamphun Valley are discussed.

HYDROLOGY OF RICELANDS

Classification of rice environments has progressed substantially in recent years. In many of the proposed classification schemes, rice cultural types are defined in relation to hydrology, but a scale factor for hydrologic environment is not explicitly expressed. Factors that affect hydrology and the rice environment may differ with the size of the area and the map scales used to delineate the boundaries of hydrologic conditions (Table 1).

This paper reviews studies on rice environment classification as related to hydrologic conditions, and proposes a new method of riceland inventory for tropical Asia.

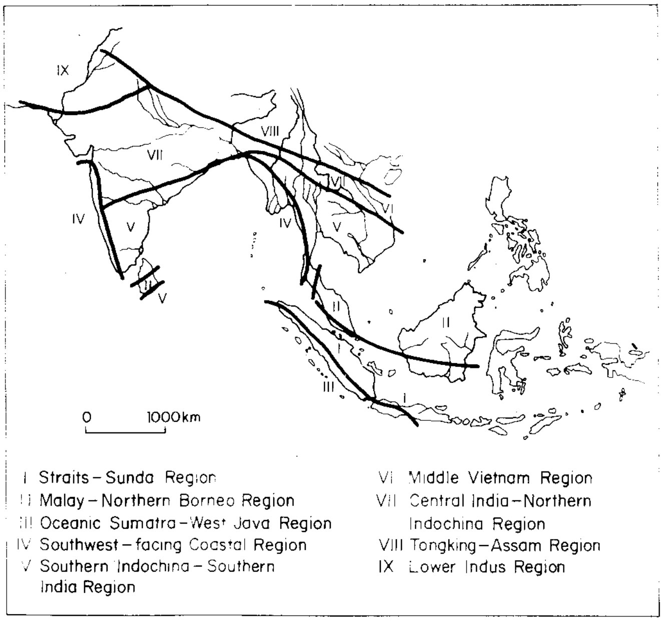
ASIA

Rice cultural characterizations in Asia are specified predominantly in relation to climate (particularly temperature) and water balance (dominated by rainfall). Physiography can be used to modify the water balance classification by allowing for the lateral movement of surface and subsurface water, irrigation potentiality, and drainage.

Kyuma (6) divided South and Southeast Asia into nine climatic regions based on water balance in riceland (Fig. 1, Table 2). His simple scheme is a general indicator of stability of rice production, rice cropping seasons, water availability, and reliability of available irrigation.

Table 1. Factors that determine riceland hydrology.

Area	Map scale	Primal factor	Secondary factor
Asia	Schematic	Climate	Physiography
Large basin	1 :4 000 000	Geomorphology	Hydrologic modification
Delta	1 :250 000 or 1 :500 000	Geomorphology	Hydrologic modification
Intermountain basin	1 :100 000 or 1 :250 000	Water resource availability	Irrigation management
Village (rainfed)	1 :10 000 or 1 :20 000	Microtopography and toposequence	Bunding Soil-water relations
Village (irrigated)	1 :10 000 or 1 :20 000	Water resource availability	Irrigation management



1. Climatic regions in South and Southeast Asia (6).

The agroecological zone scheme proposed by Panabokke (8) and refined by many scholars from Asian countries includes rainfall regime and soil groupings as classifiers. The scheme provides useful zoning maps, mainly by country, that clearly indicate present cropping systems and sequences, and also can suggest possible new cropping systems. However, because uniform classification criteria are used for the whole Asian region, local characterization is sacrificed for simplicity and uniformity and the maps lack visual comprehensiveness.

Large River Basin: The Chao Phraya River Basin

A map of rice cultural types in the Chao Phraya Basin in Thailand was generated by integrating maps of physiography, hydrology, soil morphology, rice cultural methods, yield performance, and average landholding (1) (Fig. 2, Table 3). There are six rice cultural regions, each representing homogeneity in rice culture. Regions are named by hydrologic characteristic: traditionally irrigated area, water-deficient foothills, inland flood area, barrage irrigation area, canalled lowland, and less-flooded delta.

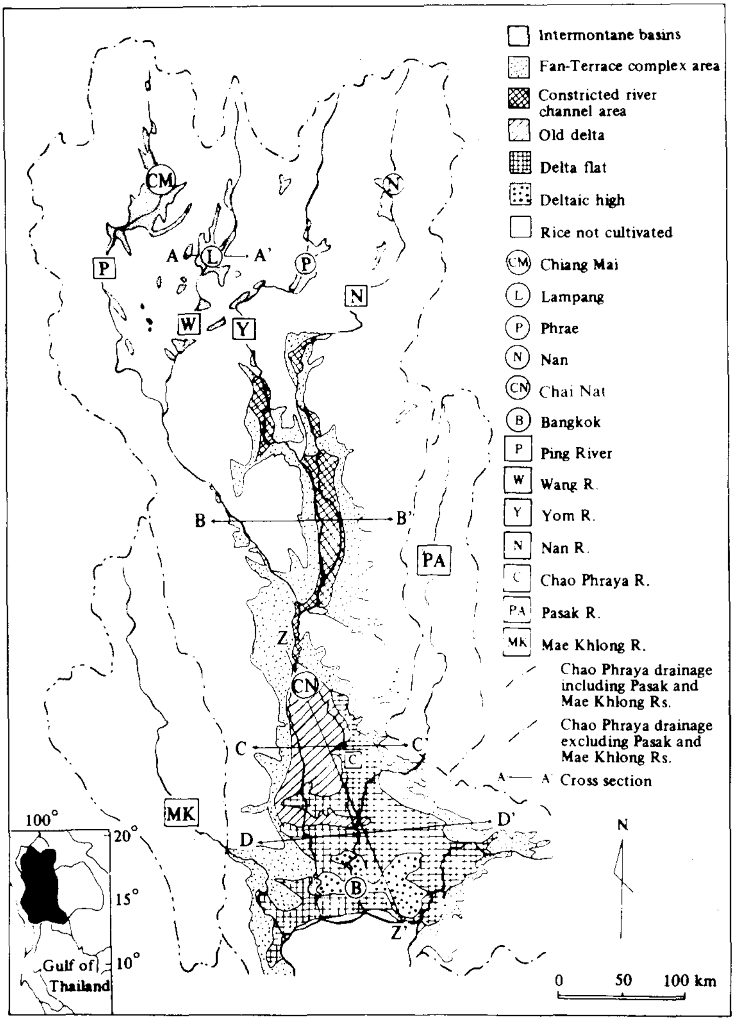
Table 2. Climatic regions in South and Southeast Asia (6).

Group	Characteristics of climate and water balance
I	Straits-Sunda Region; Humid equatorial climate with very small temperature fluctuation; minimum rainfall 100 mm in Aug and maximum 250 mm in Jan.
II	Malay-Northern Borneo Region. Humid to perhumid equatorial climate with very small temperature fluctuation; minimum rainfall 150 mm in Jul and maximum 400 mm in Nov-Dec.
III	Oceanic Sumatra-West Java Region. Perhumid equatorial climate with very small temperature fluctuation; minimum rainfall 200 mm in Sep and maximum 400 mm in Nov-Jan.
IV	Southwest-facing Coastal Region. Tropical monsoon climate with small temperature fluctuation; minimum rainfall less than 10 mm in Jan-Feb, and maximum over 550 mm in Jul.
V	Southern Indochina-Southern India Region. Tropical monsoon climate with small temperature fluctuation; minimum rainfall less than 20 mm in Feb and maximum 200 mm in Sep-Oct.
VI	Middle Vietnam Region. Tropical monsoon climate with moderate temperature fluctuation; minimum rainfall 50 mm in Mar-Apr and maximum 500 mm in Oct-Nov.
VII	Central India-Northern Indochina Region. Tropical to subtropical monsoon climate; minimum rainfall less than 10 mm in Dec and maximum 300 mm in Jul-Aug.
VIII	Tongking-Assam Region. Subtropical monsoon climate; minimum rainfall 30 mm in Dec and maximum 300 mm in Jul-Aug.
IX	Lower Indus Region. Subtropical arid climate. Slightly monsoonal with maximum rainfall 60-70 mm in Jul-Aug; for the rest of the year rainfall does not exceed 30 mm.

The hydrologic classification in this study was based on irrigation and water control:

- gravity irrigation
  - government, communal (effective)
  - communal (ineffective)
- pump irrigation
- water conservation
  - controlled (poldered)
  - uncontrolled.

This classification system gives a comprehensive picture of the hydrologic environment that is useful for specialists in water resource planning and irrigation development, rice variety improvement and rice-based cropping systems. It also is easy to delineate and comprehend because the system directly reflects local physiography.

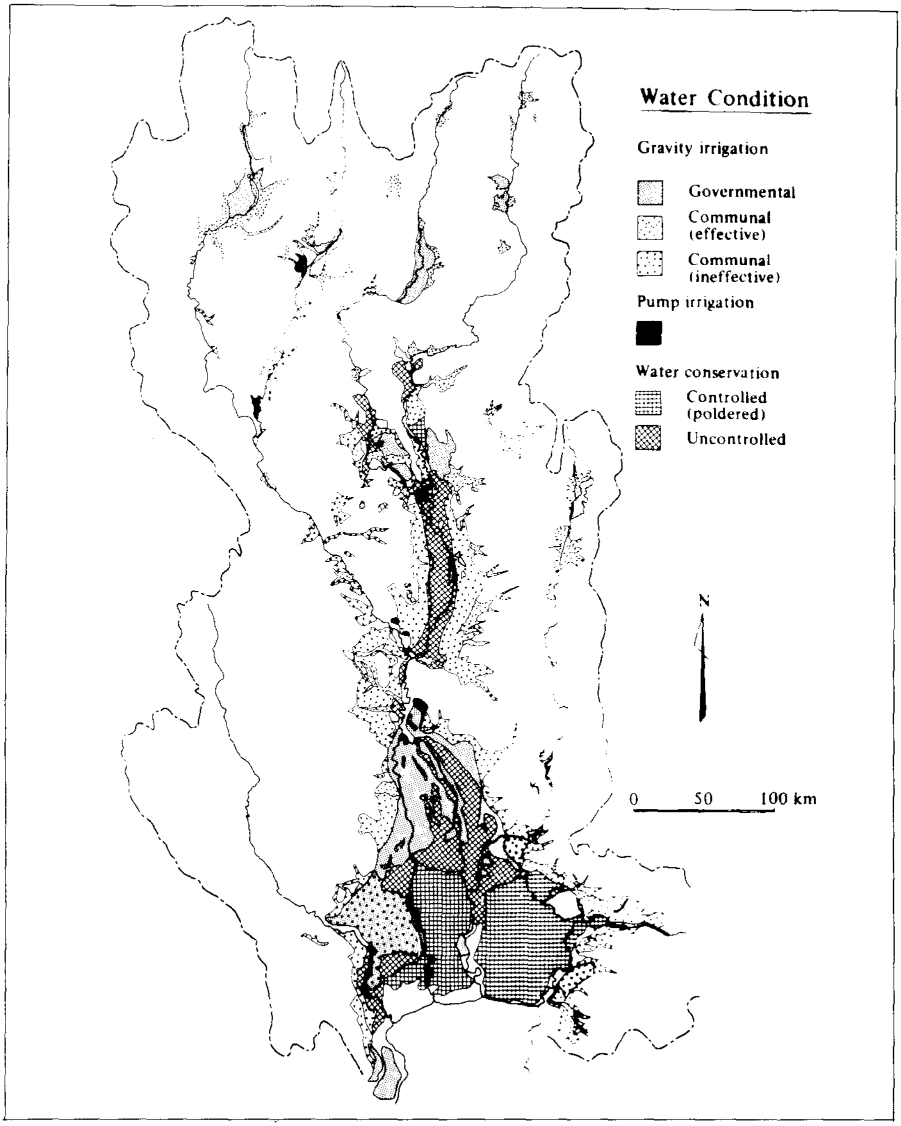


2a. Physiography of the Chao Phraya River Basin, Thailand (1).

Delta: The Chao Phraya Delta

Kaida (4,5) subdivides the Chao Phraya Delta into five agro-hydrologic regions based on hydrologic records for the main rice growing season. The classification distinguished between transplanted and broadcast rice, and allowed for transplanting date, inundation period, maximum depth of inundation, maximum inundation date, rising water rate, and drainability. The map (Fig. 3) delineates

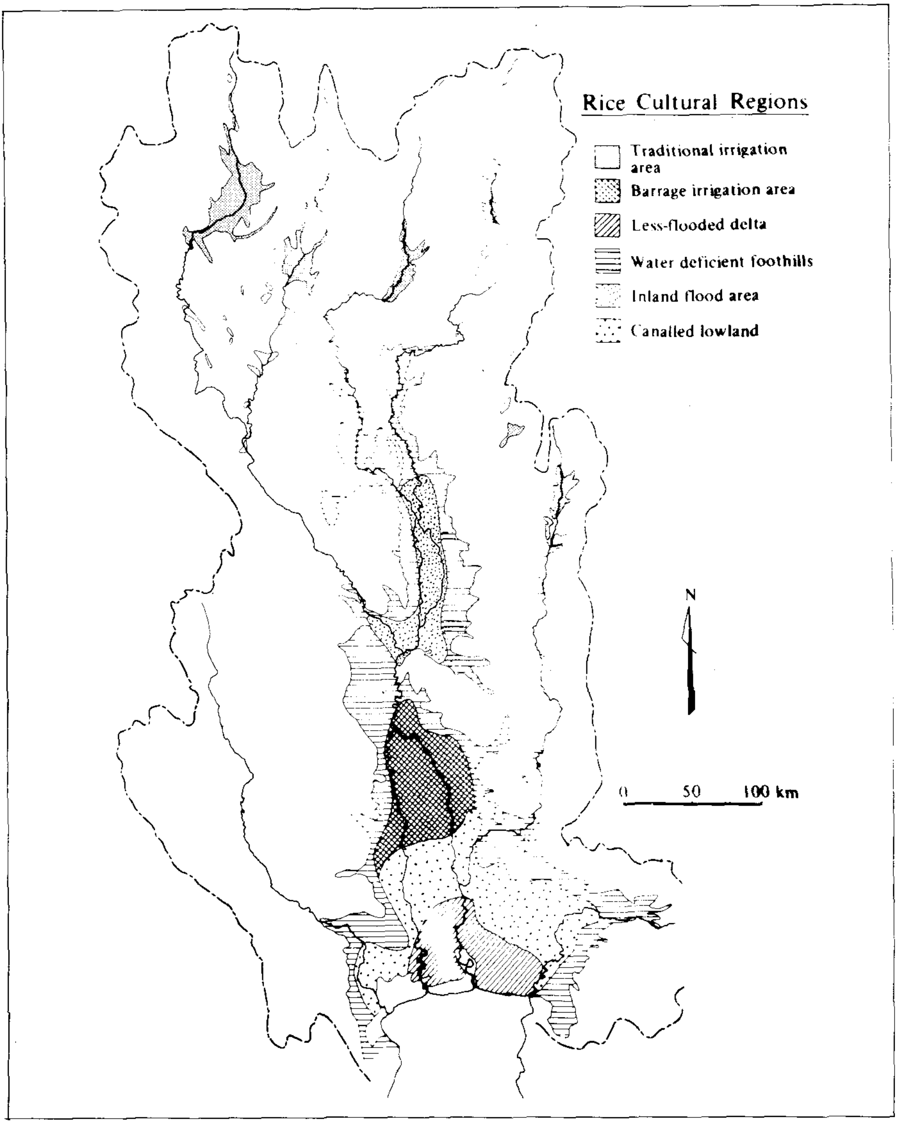
- the old delta,



2b. Hydrology of the Chao Phraya River Basin, Thailand (1).

- chains of depressions,
- the retarding basin,
- the poldered flat delta, and
- the ramified river area of the coastal zone.

Although the major classification criteria are related to water regime, the classification includes some agronomic and physiographic factors, and methods of water control and



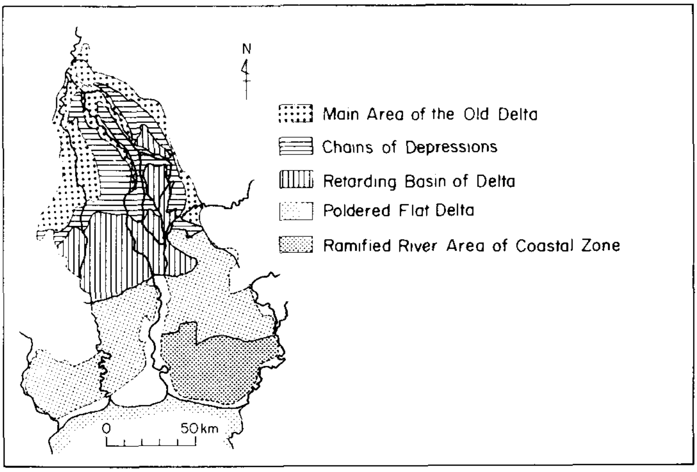
2c. Rice cultural regions in the Chao Phraya River Basin, Thailand (1).

irrigation. The names of the agrohydrologic regions reflect these additional factors.

In a huge delta with diverse, uncontrolled water regimes, hydrology is best classified in relation to the geomorphology. Based on a semidetailed geomorphologic classification of the Delta (Fig. 4), Takaya and Thiramongkol (9) inventoried 10 hydrologic units (Fig. 5). Their classifica-

Table 3. Rice cultural regions in the Chao Phraya River Basin (1).

Rice cultural region	Physiography		Water condition	Soil	fertility	Management	Rice yield (t ha^{-1})	Rice area (ha) cultivated per farm family	Rice production (t) per farm family	Approximate rice area (ha × 10^3)
Traditional irrigation area	Intermontane basin	Gravity irrigation	Governmental Communal		Medium	Transplanted	2.5-3.0	1·2	2·4	320
Water-deficient foothills	Fan-terrace complex area	Gravity irrigation	Effective Ineffective	Riverine alluvial soils	Low	Transplanted	1.0-2.5	3·4	2·7	1,310
Inland flood area	Constricted river channel area	Conservation irrigation	Uncontrolled	Riverine alluvial soils	Medium	Broadcast	1.5·2.0	4·5	6·8	200
Barrage irrigation area	Old delta	G. I.	Governmental	Riverine alluvial soils	Medium	Transplanted	1.8·2.2	3·4	5·7	80
		G. I.	Uncontrolled		High	Broadcast	1.8·2.2	3·5	6·8	310
Canalled lowland	Delta flat	Conservation irrigation	Uncontrolled	Brackish water alluvial soils	Low	Broadcast	1.0-1.5	5-7	6-10	750
Less-flooded delta	Deltaic high	Conservation irrigation	Controlled	Marine alluvial soils	High	Transplanted	1.8·2.5	3·4	7·12	280



3. Agrohydrologic regions of the Chao Phraya Delta, Thailand.

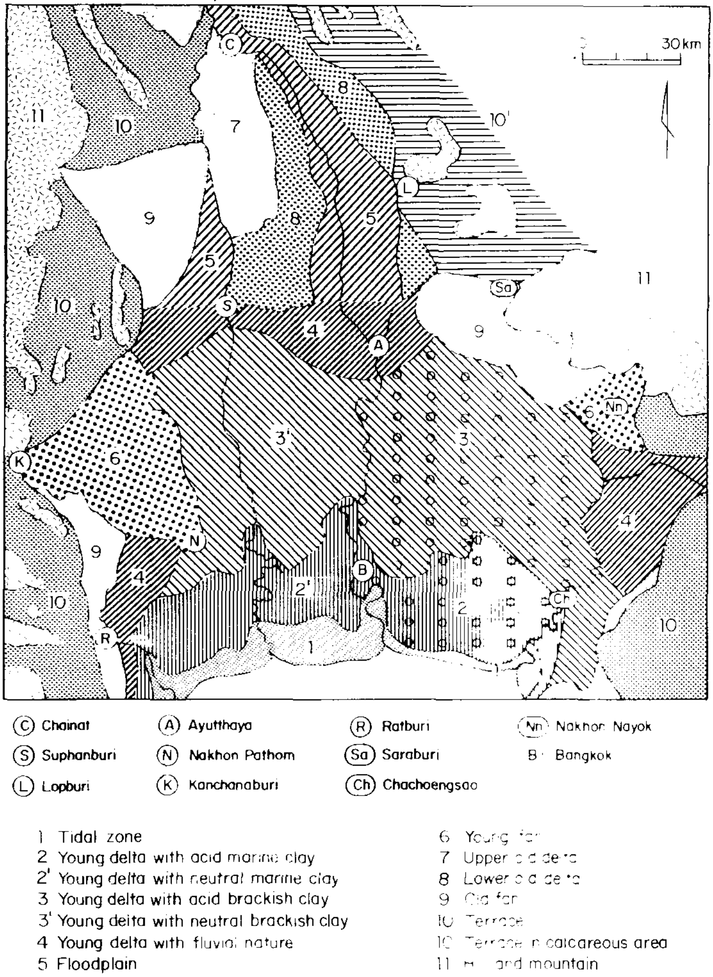
tion criteria resemble Kaida's, and are a combination of geomorphology (physiography), water control, and irrigation. The 10 hydrologic units are

- rainfed fan – terrace complex,
- irrigated fan – terrace complex,
- irrigated old delta,
- floodplain as a water conservation area,
- poldered fluvial delta,
- irrigated east bank,
- poldered west bank,
- unirrigated delta,
- protected coastal zone, and
- unprotected coastal zone.

RICELAND INVENTORY -- A DESCRIPTIVE ATLAS

We tried to develop a more useful inventory of rice land in Riceland inventory -- a descriptive atlas. The scheme seeks to inventory rice cultural units on a mesoscale (1:50,000 to 1:250,000, depending on the size of the region to be investigated), using LANDSAT imagery and extensive field surveys. The steps follow:

1. Tentative delineation of land units by interpreting LANDSAT images for different seasons.
2. Extensive field survey and interviews with farmers to collect information on rice cultural environment, agricultural practices, and performances.

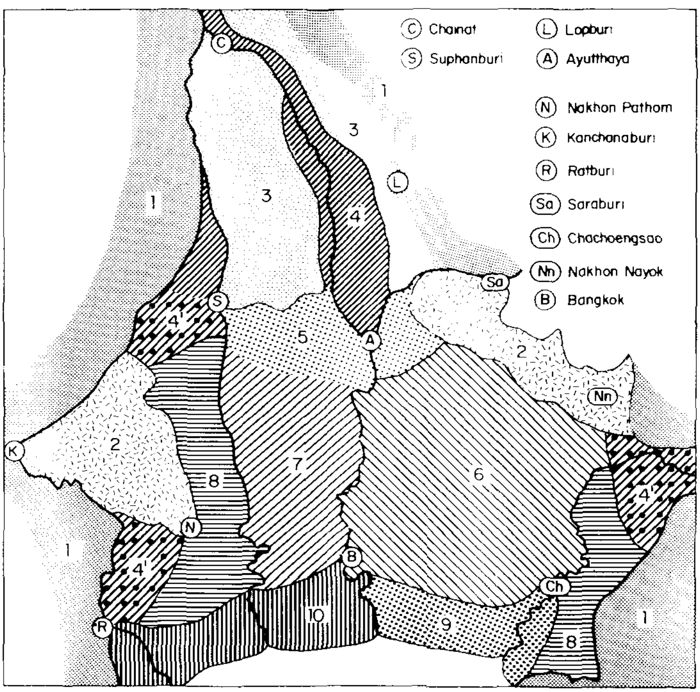


4. Semidetailed geomorphologic classification of the Chao Phraya Delta, Thailand.

3. Review of available reference material, including topographic maps, thematic maps, research reports, government documents, etc.
4. Revision of tentative unit boundaries and final inventory of land units.
5. Tentative description of each land unit based on LANDSAT images and field surveys.
6. Incorporation of the reference information.
7. Correlation of agricultural performance in the land units, and land features such as landform; soil, climate, hydrology, and irrigation; and socioeconomic aspects.

Description of land units is very important to this classification scheme. The description should be brief and pinpoint the essential and specific features of each unit. Although the description depends upon the investigator, typical items might include landform, soils, water conditions, and agricultural practices and performance. Brief notes on the history of land development, landholding statistics, transportation and marketing of products, and village landscapes may improve the description. The land units inventoried may be numbered, but it is better to name them for specific characteristics and locations, e.g., Lamphun rainfed terrace.

Note that the scheme is not equipped with solid classification criteria, although it is largely based on LANDSAT interpretation. The scheme seeks to inventory, not to classify, riceland. Land unit evaluation should be left open to potential users, who may be specialists in water resource



1 Rainfed fan-terrace complex
2 Irrigated fan-terrace complex
3 Irrigated old delta
4,4' Floodplain as a water–conservation area
5 Poldered fluvial delta
6 Irrigated east bank
7 Poldered west bank
8 Unirrigated delta
9 Protected coastal zone
10 Unprotected coastal zone

5. Hydrologic units of the Chao Phraya Delta, Thailand.

and irrigation development, rural development, rice breeding, or cropping systems research.

We inventoried the Chao Phraya Delta (119 blocks, about 1.2 million ha, were delineated [9]), the Chiang Mai-Lamphun Valley (30 land units, about 165,000 ha [7]), other intermountain basins and riverine plains in north Thailand (tentatively 30 land units, about 200,000 ha) (Lumpaopong et al, in preparation), and part of the Philippine Central Luzon Plain (23 land units, about 150,000 ha [2]).

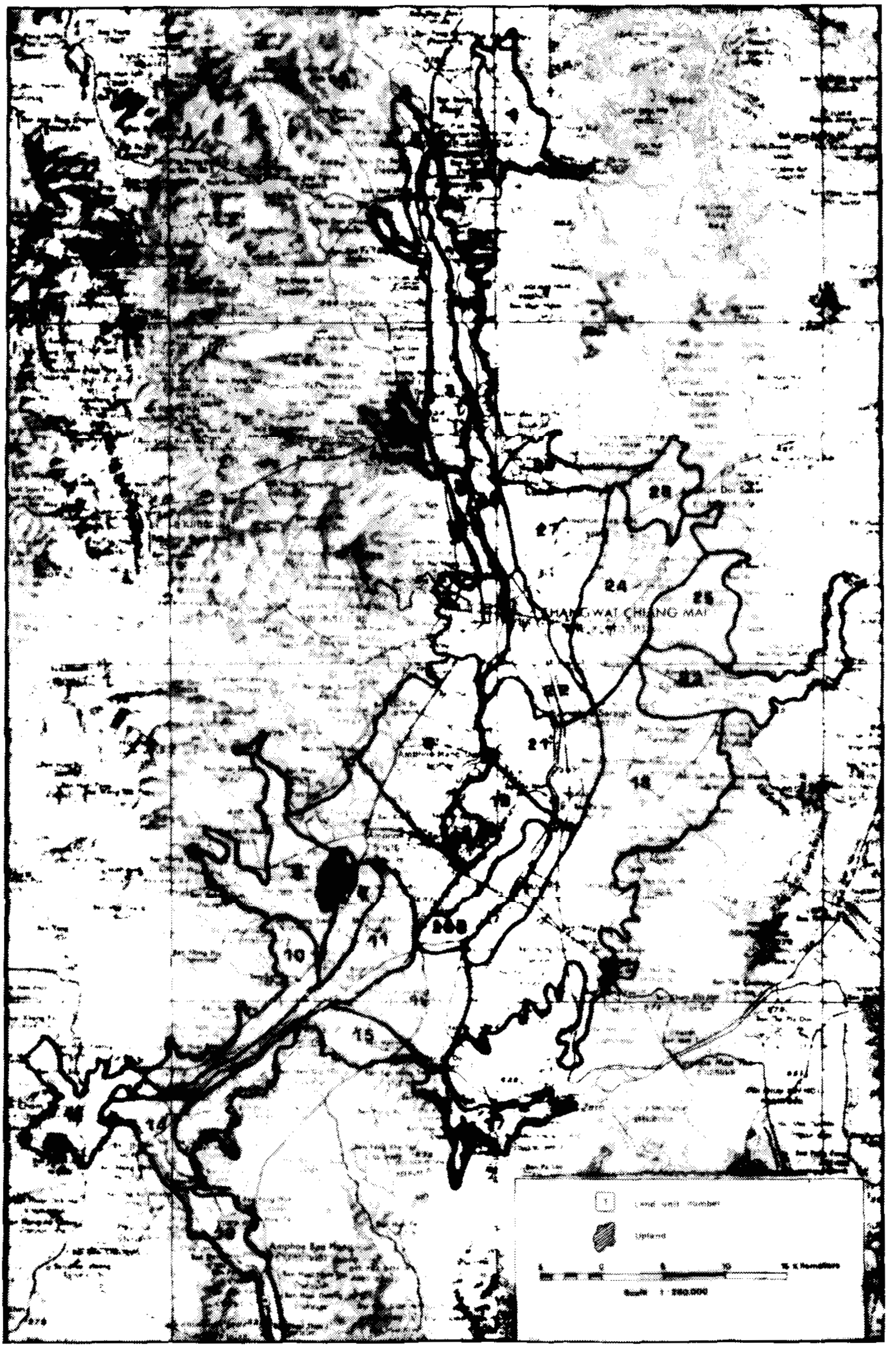
Intermountain Basin: The Chiang Mai-Lamphun Valley

The Chiang Mai-Lamphun Valley has the most advanced multiple cropping systems in Thailand. About 30% of the riceland is irrigated by communal or government gravity irrigation systems, and the rest is rainfed. There are substantial differences in crops, cropping intensity, and crop sequences, particularly in the irrigated areas.

Using the riceland inventory scheme, we identified 30 land units in the 165,000-ha valley (Fig. 6, Table 4). Six broad groups of land use were recognized: single rainfed rice, single irrigated rice, dry season rice or other crops after floods recede, one upland crop after rice, intensive garden culture after rice, and rice mixed with tree culture. Cropping was related to landform, soils, natural hydrology (soil drainage and flooding regimes), and irrigation (reliability of irrigation systems, dependability of river water, and sources of supplementary water) (Table 5).

Single cropped rainfed and irrigated rice are planted on low terraces or the fan terrace complex, which we classified as water-deficient foothills. The major constraint to more intensive land use in the rainfed area is limited water availability early in dry season. In irrigated areas, it is poor operation of state irrigation projects. Landform and soils do not limit intensified land use, except where soils are fine-textured clays that harden and crack in dry season. In the floodplain, such land has irregular shallow to moderately deep flooding, which may be prolonged in high rainfall years.

Dry season rice and upland crops following rice also are grown on the floodplain, but in greatly differing soils and microtopography. More than half of the dry season rice area is in the depression. Soil profile is less developed and fields are subject to a wide range of flooding regimes. Soil is poorly drained, and most of the area is used for rice or other annual crops only after floods recede. Much of



6. Riceland units in the Chiang Mai-Lamphun Valley, Thailand.

Table 4. Riceland units in the Chiang Mai-Lamphun Valley.

Land unit no.	Name	Area	
		ha	%
1	Chao Lae basin	4,260	2.6
2	Upper Mae Taeng	1,550	0.9
3	Mae Taeng irrigated	5,860	3.6
4	Mae Rim valley	1,600	1.0
5	Mae Yuak terrace	1,100	0.7
6	Hang Dong fan and terrace complex	9,740	5.9
7	Pa Tun terrace	7,150	4.3
8	Mae Khan basin	6,350	3.9
9	Lower San Pa Tong terrace	2,260	1.4
10	Thung Pui terrace	3,250	2.0
11	Doi Noi floodplain	6,260	3.8
12	Chom Thong valley	5,850	3.6
13	Upper Ban Hong valley	3,550	2.2
14	Lower Ban Hong valley	3,100	1.9
15	Southern rainfed terrace	5,810	3.5
16	Mae Tha fan	5,700	3.5
17	Mae Tha valley	3,300	2.0
18	Lamphun rainfed terrace	23,950	14.5
19	Ban Nong Chang Keun orchard	6,100	3.7
20	Mae Ping kao plain	4,590	2.8
21	Saraphi plain	7,340	4.5
22	Chiang Mai suburban	4,750	2.9
23	San Kam Phaeng fan	7,300	4.4
24	Mae Kuang irrigated	9,060	5.5
25	San Khao Khaep klang	4,500	2.7
26	San Um-Mae Kuang irrigated	2,610	1.6
27	San Sai fan	7,250	4.4
28	San Phee Sua	2,800	1.7
29	Mae Jo terrace	2,850	1.7
30	Mae Faek irrigated	5,060	3.1
	Total	164,860	100

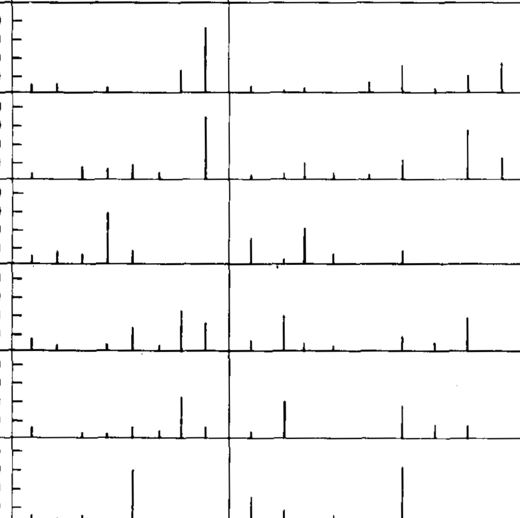
the rice – uplandcrop area is on the plain. The wider plain and levee complex is planted to rice and fruit trees. The land is less subject to severe flooding, and has better drained soils.

About 10% of the valley is used for intensive garden culture after rice. Triple cropping is common. The third crop is grown in a limited area where individual farmers use dug or tube wells for supplemental irrigation in addition to communal, weir irrigation systems. Readily usable groundwa – ter generally is available where the ratio of catchment to rice (C:R) exceeds 10.

Rice – upland cropping and rice plus intensive garden culture are found in a wide range of physiographic units and

Table 5. Agricultural land use as related to land and hydrologic characteristics in the Chiang Mai-Lamphun Valley, Thailand.

Land Characteristic — Physiographic unit: Floodplain (Complex, Levee, Middle, Depression), Plain, Fan, Fan-terrace, Terrace; Soil: Typic Ustifluvents, Entisols, Aeric Tropaquepts, Vertic Tropaquepts, Aquic Dystropepts, Typic Tropaqualfs, Aeric Tropaqualfs, Typic Ochraqualfs, Typic Paleaquults



Agricultural land use	Land unit no.	Per cent	Natural hydrology: Soil drainage: Poor	Somewhat poor	Moderately good	Flooding regime[b]: 1	2	3	Irrigation[a]: Traditional	Government	Supplementary water: Dug wells	Tube wells
Single rainfed rice	15, 18	80 60 40 20	√	–	√	–	–	–	–	–	–	–
Single irrigated rice	20, 24	80 60 40 20	√	–	√	√	√			+	–	
Dry season rice or other annual crop after flood	11	80 60 40 20	√	√	–	√	√	√	++	+	–	–
One upland crop after rice	1, 2, 3, 4, 5, 6, 7, 9, 10, 17, 23, 25, 26, 27, 28, 29, 30	80 60 40 20	√	–	–	√	√	–	–	++	–	–
Intensive garden culture after rice	8, 12, 13, 14, 16	80 60 40 20	√	√	–	√	√	–	+-	–	√	√
Rice mixed with tree culture	19, 21, 22	80 60 40 20	√	–	√	–	√	·	++	++		–

[a]Stability of water supply: – = unstable, + = fairly stable, ++ = stable

[b]Flooding regimes: 1 = shallow, irregular and brief; 2 = shallow to moderately deep, irregular and prolonged, 3 = deep, irregular, and deep

Table 6. Microphysiography units and related hydrologic regimes in the rice fields of a small sample village in northeast Thailand.

Physiographic unit	Hydrologic regime during		
	Flood years	Normal years	Drought years
Hill-valley system			
Valley			
Hollow	Flood	Poor	Good
Bottom	Flood	Good	Good
Headslope	Fair	Good	Poor
Sideslope	Fair	Fair	Drought
Washout	Good	Good	Poor
Top	Fair	Poor	Drought
Plain-trough system			
Channel	Flood	Good	Fair
Trough			
Hollow	Flood	Poor	Good
Bottom	Flood	Good	Good
Headslope	Poor	Good	Fair
Sideslope	Fair	Fair	Drought
Washout	Poor	Fair	Fair
Remnant flat	Flood	Fair	Poor
Shallow trough	Flood	Fair	Fair
Elevation			
Levee	Good	Fair	Drought
Flat	Fair	Fair	Drought
Ridge	Fair	Poor	Drought

soils. A common feature is poorly drained soils that are subject to relatively brief, shallow flooding.

Irrigation reliability determines the diversity of land use in the valley. Stability of irrigation generally is governed by the river flow in the early dry season and operation level and maintenance. C:R is a rough, but useful indicator of stability. If the ratio is larger than 10, diversion irrigation is dependable well into the early dry season, and shallow and readily available groundwater can be used. If C:R is less than 10, surface and groundwater may be undependable in dry season.

A village or equivalent small area

Classification schemes for the hydrology of small rice areas at a large map scale may vary with the specific characteristics of the area. Classifications of irrigated and rainfed ricelands can be quite different.

The hydrology of rainfed land generally is controlled by local microphysiography, or toposequence. Table 6 shows a microphysiography classification scheme in relation to hydrology in a small village in northeast Thailand (3). The village rice fields are located in the plain–troughland system along the Chi River, which occasionally floods, and in the hill–valleyland system. The fields are predominantly rainfed.

Different rice field water regimes are likely to be reflected by variety, plowing time and land preparation timing, transplanting and flowering date, yield, drought and flood hazards, and in landholding and division of land for inheritance. Villagers may have a special schedule for rice growing, and use different rice varieties depending upon the elevation of their fields. In the sample village, many farmers own a long, narrow tract of land stretching from the highest elevation to the lowest. Apparently, this landholding pattern facilitates scheduling of family labor and modifies the effect of severe water regime, including flooding and drought. Farmers expect to harvest rice at least on the higher land in flood years, and in the lower tracts in drought years. The system is meant to minimize risk, not maximize yields.

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SOIL-WATER RELATIONS IN RICE-BASED CROPPING SYSTEMS

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ABSTRACT

Soil-water relations affect rice-based cropping systems at two levels, Water content in the plow layer determines cultural operations. Soil that is too dry delays tillage or exceeds the work capacity of common farm power units. Soil that is too wet reduces tillage quality and affects timeliness of cultural operations.

Soil water also determines crop growth. The paper gives an example of the effect of water status on cowpea yield. The close relation between evapotranspiration and cowpea yield is used to examine long-term yield variability at four sites in northwest Sri Lanka. Effects of moisture on crop establishment and early growth are discussed. Excess moisture is important to dryland crops, especially during emergence and early crop development.

SOIL-WATER RELATIONS IN RICE-BASED CROPPING SYSTEMS

There are many opportunities to increase cropping frequency in tropical, rice-growing Asia (10, 11). As scientists and farmers add dryland crops to cropping sequences that are dominated by monsoonal lowland rice, rainfall and its interaction with soil properties and terrain features become important. Although rainfall and transpiration directly influence crop physiology, there also are important effects of rainfall on field operations and temporary flooding. A simple decision diagram (Fig. 1) based on 4 yr of research in 5 villages in Central Luzon, Philippines, shows that before field crops can use soil water, they must first be planted.

In this paper we describe and illustrate important soil-water relations in rice-based cropping systems.

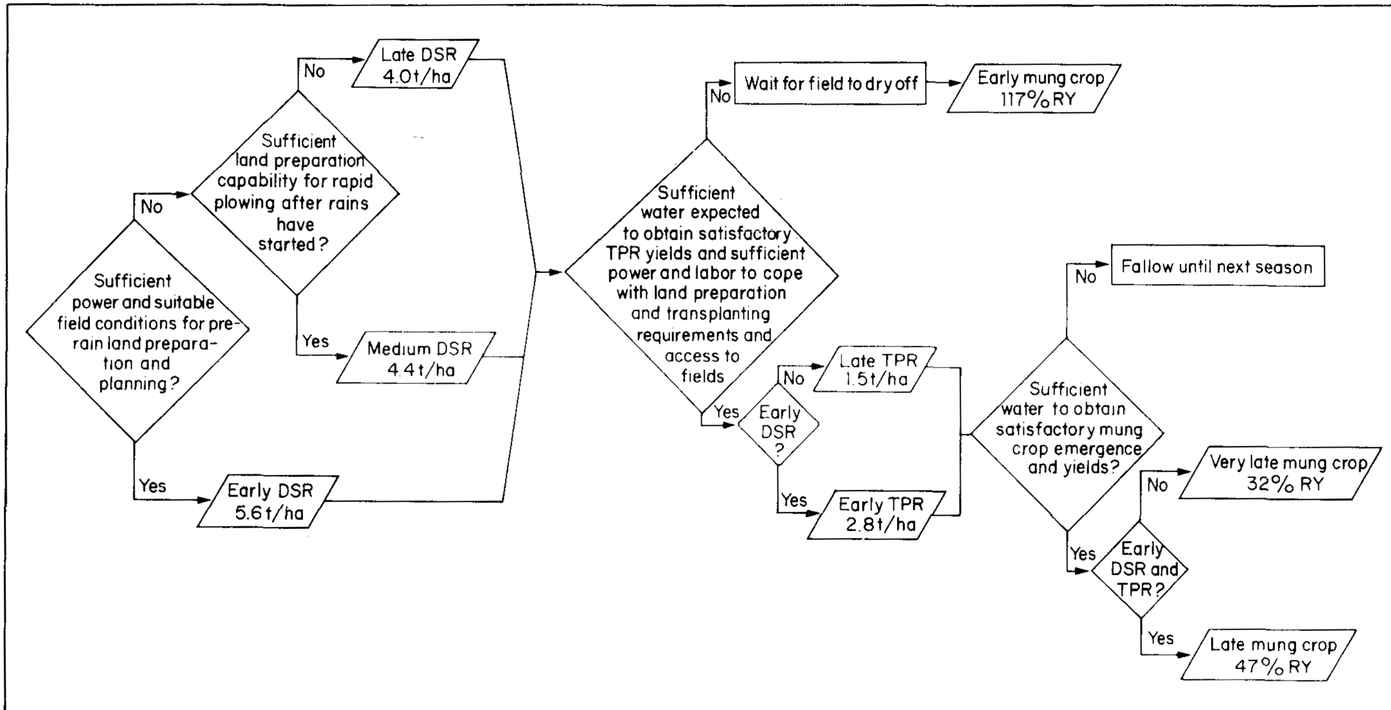
SOIL WATER AND FIELD OPERATIONS

The major soil physical factors that affect the quality of and energy required for tillage are cohesion, adhesion, shear, and compression. They are strongly affected by soil water content. Draft resistance is lowest somewhere below the plastic limit, but as soil dries, the shattering action of tillage diminishes. Conversely, if a soil is puddled before plowing, cohesion increases as soil dries. High cohesiveness makes dry plowing of previously puddled soil difficult, both in terms of operation and achievement of quality. Although we are more concerned about soil being too dry, wetness also is important, especially to dryland crops and where heavy rains are possible.

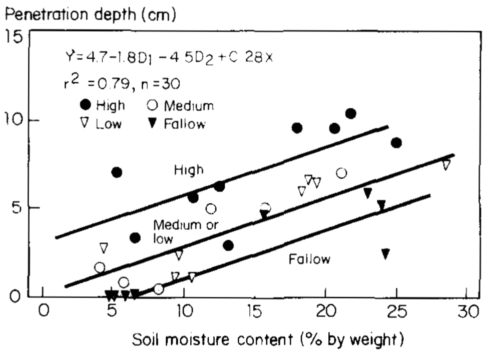
Dry field conditions

Because the farmer's capacity to prepare land and to plant is relatively fixed, field moisture is important. Figure 1, based on a cropping systems project in Manaoag, Pangasinan, Philippines, illustrates how tillage and planting operations for crops in a two- or three-crop sequence are influenced by soil moisture. Timeliness also is important for effective weed control.

The practical importance of soil moisture is illustrated in Figure 2, which shows how depth of penetration of a static-tip penetrometer increased with soil moisture content. Most farmers in this region grow two crops, although few grow two rice crops. Soils were especially hard late in



1. Schematic diagram for determining which cropping sequence can be planted. Based on a project conducted in Manaoag, Pangasinan, Philippines. DSR = dry seeded rice, TPR = transplanted rice, RY = yield relative to 3 highest yielding entries in researcher-managed variety trials (22).

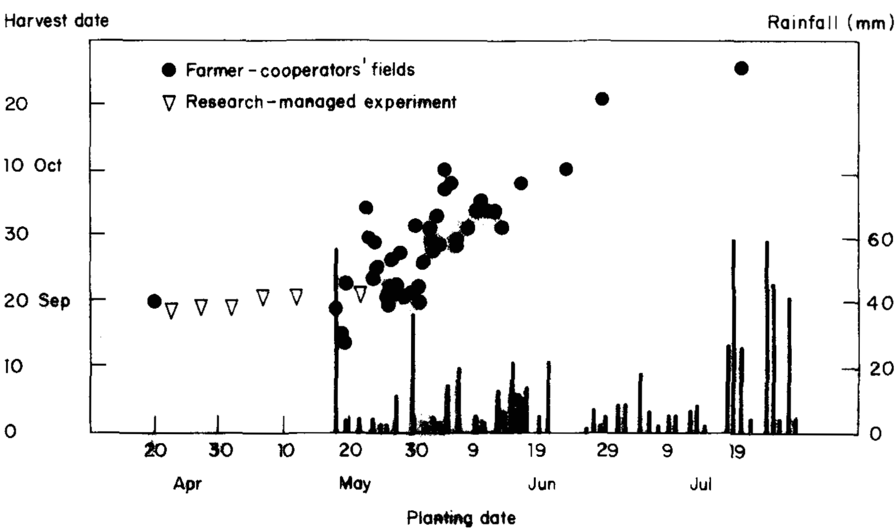


2. Effect of soil moisture and preceding season tillage intensity on depth to penetrometer resistance of 0.8 MPa, Manaoag, Pangasinan, Philippines (22). D_1 and D_2 are dummy variables for preceding season tillage intensity.

dry season if they were not fallowed throughout the dry season.

In the study year, farmers waited for rain before plowing with animal-drawn equipment, but researchers used a hand tractor to prepare land and plant before the rains (Fig. 3). Because farmers waited until rain reduced soil strength, harvest was later than when a hand tractor was used. When the first crop was planted late, second rice crop fields were low (Table 1).

Figure 4 shows early wet season soil moisture conditions for extreme years in a drought- and submergence-prone environment. The fields are on nearly level terrain, with a gradient of less than 1 m/km. Constraints of water manage-

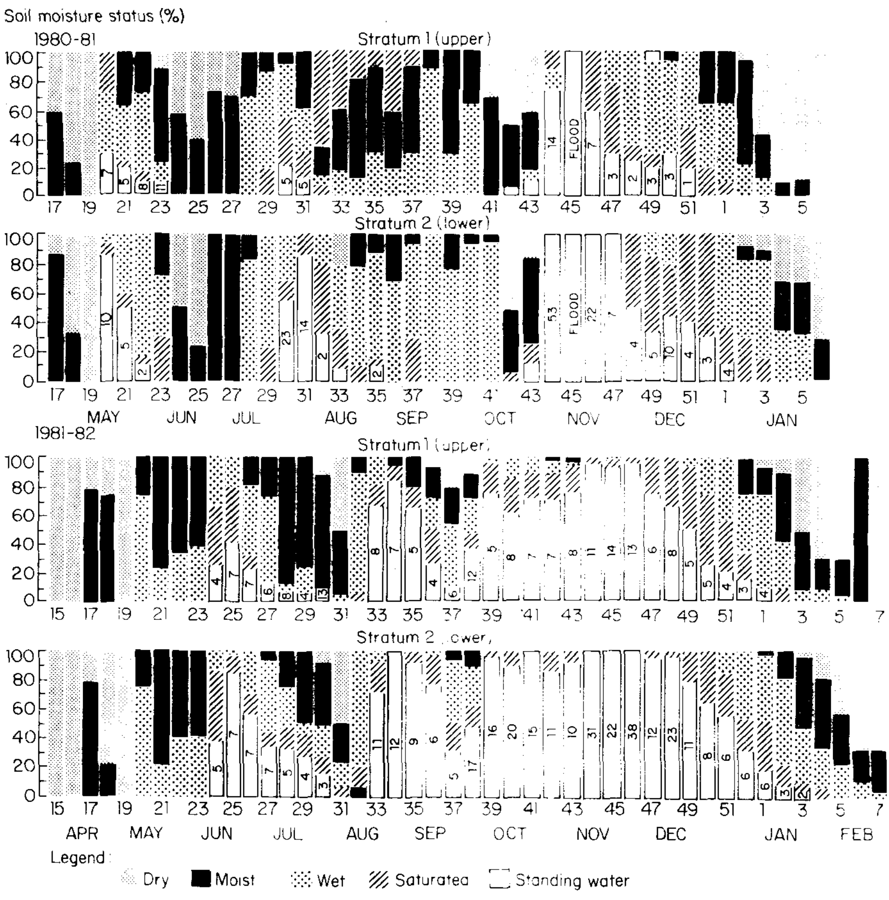


3. Dry seeded rice planting and harvest dates in 48 farmer-cooperator fields and in an experiment on a farmer's field, and daily rainfall during the planting period, 1977, Manaoag, Pangasinan, Philippines (19).

Table 1. Mean yields of dry seeded rice (DSR) and transplanted rice (TPR) by period of DSR seeding, 1977 (21).

DSR seeding period	Rough rice yield (t/ha)		n^a
	DSR	TPR	
21 May and earlier	5.3	4.0	6
22 May-31 May	4.8	2.4	18
1 Jun and later	4.1	1.5	24

[a]n = number of observations.



4. Surface soil-moisture status as percent of observed fields (16/stratum) in 2 wet seasons (1980-81 and 1981-82). Solana, Cagayan, Philippines. Moisture states were scored as follows: dry =too dry to be filled for upland crops; wet = too wet to be tilled for upland crops but free water is not visible in footprints, buffalo tracks, or other shallow depressions; saturated = free water is visible but flooding is not continuous across the field; standing water = flooding is continuous across field; moist = wetter than dry but drier than wet. Numbers in open bars Indicate mean standing water in fields on which flooding is continuous across the field (10).

ment in this environment usually prevent farmers from successfully following experimental double-cropping calendars (8). Although mungbean commonly was planted on schedule (early in wet season) in the upper stratum, crops often were damaged by periods of excess moisture. Fields were too dry for direct-seeding rice on schedule. When modern rice varieties were seeded late, flooding in September or October often ruined the crop.

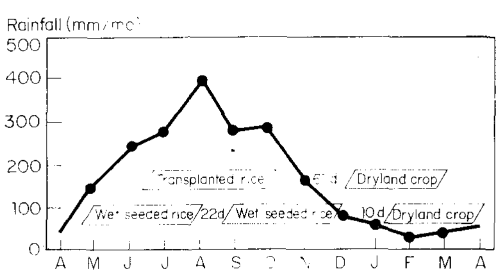
In this environment, a combination of dry conditions, which delayed planting, followed by increasing flood hazard, created a 3- to 4-mo period (May-Aug) when the cultivation of modern varieties was risky.

Wet field conditions

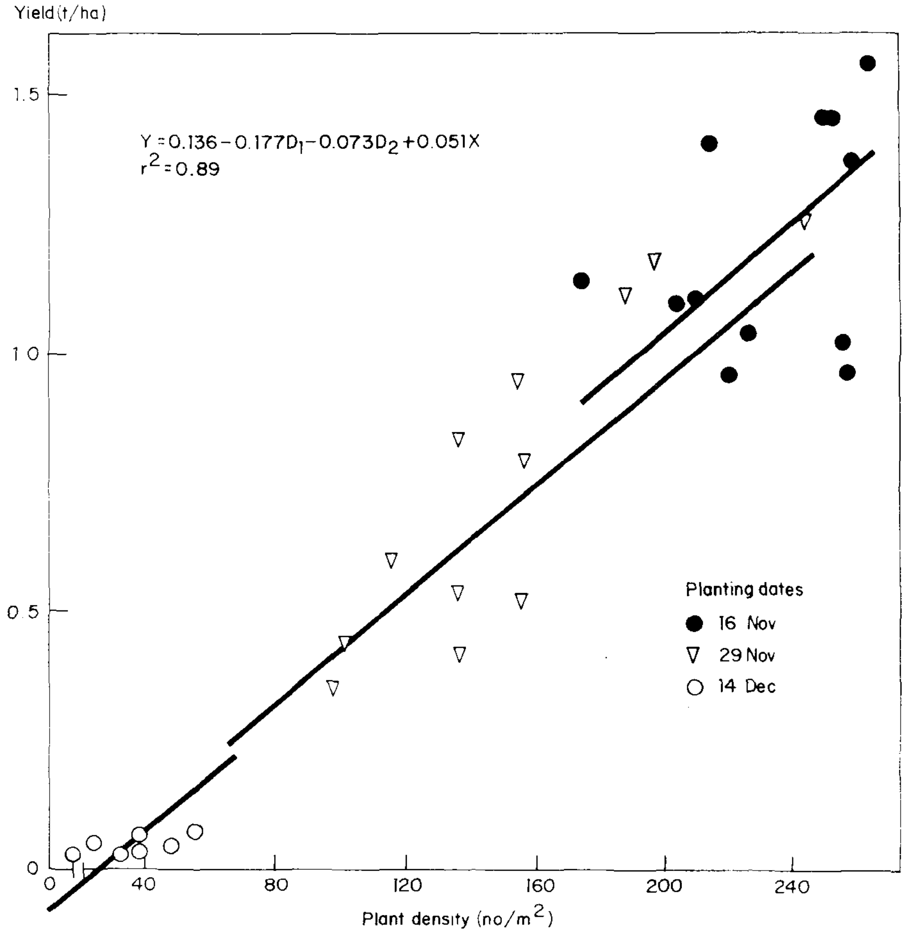
Although soil seldom is too wet to till for rice, fields can be too wet to till for dryland crops. When soils are wet, plowing has no shattering action and long, nearly continuous furrow slices (ribbons) of soil are turned over. They dry to large, massive, hard clods that are hard to break by secondary tillage. Such tillage conditions encourage farmers to delay land preparation for dryland crops following lowland rice.

For example, the time interval between successive rice crops in Iloilo, Philippines, averaged 22 d, but dryland crops were planted an average 61 d after rice (Fig. 5). Rainfall is quite heavy during this time, and even with good tilth, aeration probably is too low in many years for satisfactory germination and seedling growth.

Soil bearing capacities and rolling resistances necessary for mechanized tillage are adversely affected by high soil water content. Interrow cultivation also is hampered. Moreover, many weeds grow well with excess moisture, and weed pressure can destroy a dryland crop.



5. Mean turnaround period between crops in rice - dryland crop and rice - rice - dry - land crop sequences, and mean monthly rainfall. Iloilo, Philippines, 1975-76 crop year. The numbers indicate days from harvest to planting (21).



6. Effect of planting date on plant density and grain yield of mungbean, Manaoag, Pangasinan, Philippines, 1979 (21).

SOIL WATER AND CROP PRODUCTIVITY

Crop-soil-water relations influence germination, seedling emergence, root and leaf development, potential seed size, and photosynthetic rate during seed filling.

Crop establishment

Figure 6 gives an example of the effect of planting delay on plant density and mungbean yield. Only 33 mm of rain fell during growing season, most on 16 Nov (10 mm) and 22–23 Dec (15 m). Even the 22–23 Dec rain had little effect because the soil surface was very dry and hot. Sowing delay reduced plant emergence. There was, however, ample water in the soil profile, as demonstrated by 1.5 t/ha mungbean yields. These crops grew almost entirely on residual soil water.

Aspects of soil-water relations and seed imbibition and germination processes were discussed by Hadas and Russo (9). and Collis-George and Hector (6), Choudhary and Baker (5) discussed seed environment in relation to seed furrow shape and soil moisture. However, because of the moisture regime and tillage used for rice cultivation, careful diagnostic studies of soil-water-seed and soil-water-field operation relations for a range of crops and soil-environment combinations will be necessary before significant advances are made in land preparation and seeding techniques for dryland crops grown before or after lowland rice.

Transpiration

Major processes of water loss in rice-based cropping systems are transpiration from crops and weeds, water consumption in land preparation, percolation and seepage during rice cropping, and soil evaporation between crop phases or during the dryland crop. Because crop yield relates closely to seasonal totals of transpired water, maintenance of transpiration at the potential rate by a fully developed, healthy crop canopy is the goal of both farmers and scientists.

Cropping systems researchers seek to develop cropping patterns that are acceptable to farmers and increase productivity within the limits of water available for transpiration. Although productivity may increase, year-to-year yield variability may also increase. Field testing of alternative cropping patterns lasts only a few years. Relations between soil moisture and yields are therefore sought so long-term risks associated with various sequences can be assessed.

Briggs and Shantz (3) and later, others, demonstrated a relationship between crop water requirement and wheat yields, and noted that it was independent of variety and fertility. The essence of this relationship is parallelism between transpiration and biomass production (7).

The actual evapotranspiration (ETa)-yield relationship is effective for practical cropping systems research because ETa is relatively easy to estimate from soil moisture data. From the relationship and from meteorological records, it is possible to reconstruct the water balance for years when soil moisture depletion is not measured. The sum of ETa can be used to predict crop yields.

This procedure was used to predict rainfed cowpea yields for northwest Sri Lanka in a manner similar to that previously used to predict rainfed rice yields (1, 2, 25). Dominant cropping patterns in this region are irrigated rice in both seasons, and rainfed rice in wet season on poorly drained Grumusols (Vertisols) and yellow Latosols. Sesame, cowpea, black gram, banana, cashew, and mango are grown on red and sometimes on yellow Latosols. Where tubewell irrigation is available, high-value crops such as chili, onion, potato, aubergine (<u>brinjal</u>), and grapes are grown (21).

Research on soybean, maize, and cowpea currently is proceeding on the poorly drained, drought-prone Red-Brown soils of the Mahaweli Development System in east-central Sri Lanka. Cowpea is a dominant dryland crop in this zone. It is grown as a slash and burn crop and as a dryland crop with irrigated rice. Because cowpea is drought tolerant, it was considered also to be the best indicator crop for rainfed agriculture in newly settled areas in the northwest dry zone.

Field trials were conducted at Vananthavillu Agricultural Research Station (8° 12'N, 79° 53'E) in the northwest Sri Lankan dry zone on yellow Latosols (Unesco-FAO Achroic Luvisols) sandy-loam soils of CEC 3.4 meq/100 g, 0.04% N, 0.26% C, and 26 ppm P (Bray). Rainfall was bimodal with major rains from October to January and minor rains from March to May. Rainfall is 900-1500 mm/yr.

Cowpea cultivars MI-35 (75 d) and EE-3 (90 d) were planted early-, mid-, and late-season to produce a range of yields. Crops were irrigated for 10 d after planting to ensure good stands. The first two plantings were there after rainfed. Half of the third planting and all March-May plantings were irrigated. Irrigation was applied to return soil moisture to field capacity from 75% depletion in the root zone (in both seasons), 75% depletion in the top 30 cm, and 50% depletion in the top 30 cm (in March-May only).

Soil moisture was monitored to 3-m depth with a neutron moderation moisture meter (Wallingford IH II) and gravimetric soil moisture samples were taken from 0 to 15 cm.

A method by which parallelism of ETa and dry matter accumulation is used to predict crop opportunity, failures, and yields in a rice-rice-grain legume pattern has been described (1, 2, 18). By carefully monitoring soil water, especially during the unsaturated phase, ETa was estimated and used to predict rice yields. Evaporation from the water surface was also measured, so that transpiration (rather than ETa) could be directly related to total dry matter at harvest.

In estimating ETa, assumptions were:

- no surface runoff -- soils had high infiltration rates and fields were bunded;
- ETa was equal to pan evaporation during brief periods of drainage when estimates from the moisture profile change were impossible; and
- no capillary rise into the root zone because the water table was more than 10 m deep.

The data points in the yield–ETa relationships for plots with incomplete stand were well off the line (Fig. 7). Their deviation from the line suggests that water requirement prior to crop planting should be included in the regression.

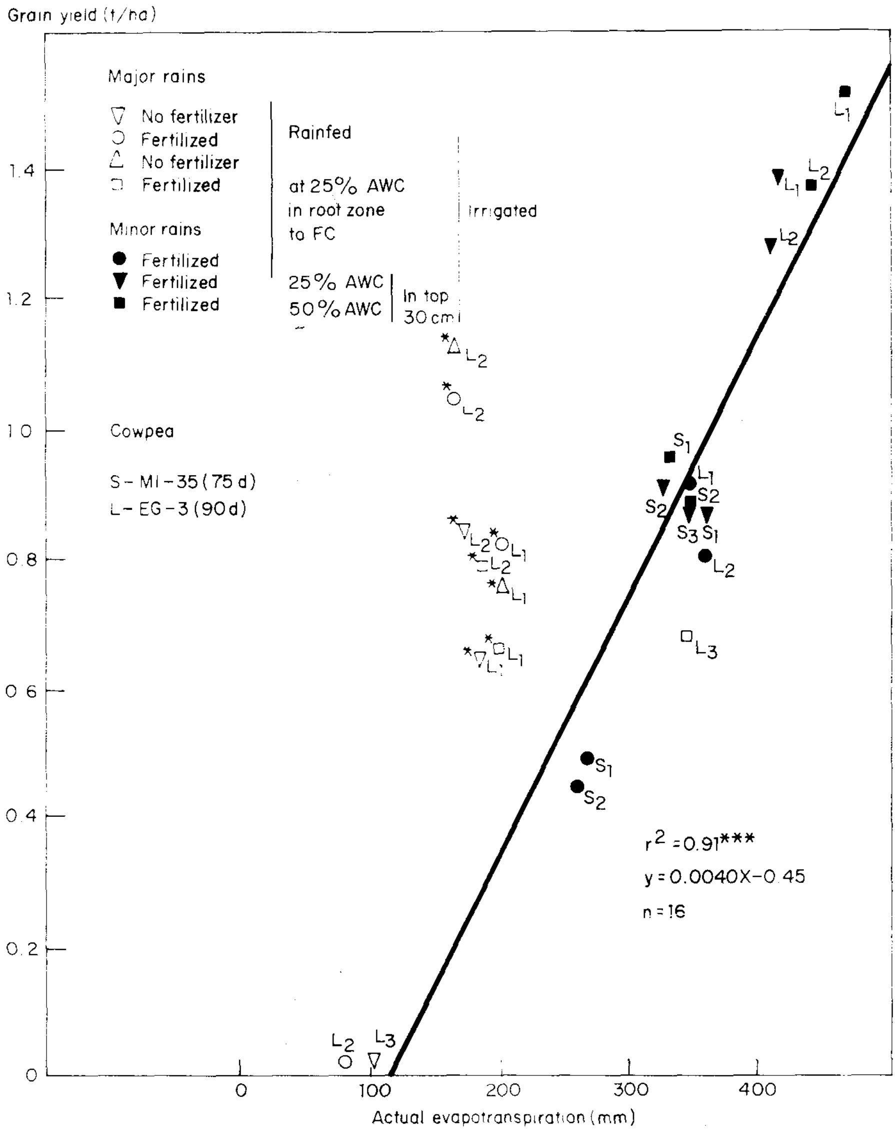
The starting point for yield prediction was the WATBAL simulation of Keig and McAlpine (13) as used by Reddy (20). The model was used to predict ETa for the study area with only rainfall and Penman ETrc (reference crop) inputs. ETa values were then validated against measured values. Agreement was good for ETa near maximum and zero moisture, but limited data at intermediate values prevented proper model validation. On these soils, transition from maximum to zero available water is rapid.

The WATBAL model was augmented by including the relation between ETa and yield: no yield up to 112 mm ETa, and 0.0040 t/ha per mm thereafter. The rainfall requirement for adequate stand also was included.

Table 2 shows that the highest predicted failure rate, 0.2 or once in 5 yr, occurs in Marichchakkudai, in the middle of the dry zone. The risk of crop failure was least in the north (Paranthan), and intermediate in the west (Puttalam). Most failure was caused by poor rains at planting, which reduced establishment.

In Vananthavillu under farmer management, yields were 0.36 t/ha. Recommended crop management was used in the simulation, and yields were 1.23 t/ha. With farmer management, cowpea cultivation may only be justified in the north where, with adequate moisture at planting, yield, would increase considerably because rainfall generally is adequate to prevent subsequent crop loss. This information is pertinent to the rice–cowpeasystem where there is opportunity for cowpea to be planted when the profile is at field capacity.

To determine the water requirements for adequate crop stand, 5, 10, 15, 20, 30, or 40 mm water was applied to soil near to permanent wilting. The trial at Vananthavillu was repeated with the same water quantities applied in 2 equal doses 2 d apart. Cowpea was planted on four dates, each



7. The cowpea yield-evapotranspiration relationship for 2 cultivars, 3 planting dates (suffixed), and 2 seasons. Vananthavillu Agricultural Research Station, Sri Lanka, 1981-82. *Plots with incomplete stand were excluded from the regression. AWC = avaliable water-holding capacity, FC =field capacity, L = long duration, S = short duration.

after an early monsoon shower, to corroborate findings from the first trials. Crop stand was measured 20 d after sowing. Responses to irrigation showed that for a 90% stand to survive at least 20 d, 20 mm of irrigation (or rainfall) is

Table 2. Simulated rainfed cowpea yields and frequency of crop failure for the Sri Lankan northwest dry zone.

Meteorological station	Record (yr)	Yield (t/ha)	Standard deviation (t/ha)	Frequency (%) of		
				Crop failure	Poor stand	Crop loss
Puttalam	29	0.86	0.37	14	7	7
Marichchakkudai	24	0.79	0.43	21	21	0
Murunkan	29	0.88	0.36	10	7	4
Paranthan	31	1.07	0.31	7	7	0

necessary within 3 d of planting. This was consistent with estimates made for West Africa (22, 23).

During the field trials, data were collected for leaf area index, leaf transpiration rate, leaf diffusive resistance, leaf water potential, canopy temperature, and dry matter partition, but the only data required for the model was the meteorological record for Penman ETrc or pan evaporation data, yield, and the soil moisture profile. The collected data were adequate for a complex model that might be used for Reddy's ICSWAB simulation (20) of single-crop, double-crop, and relay-crop systems. However, the simple model served the intended purpose.

Excess moisture

Although rice grows well in soils that are largely without oxygen, dryland crops do not. The chemical and physical conditions created to grow lowland rice are hostile to other major field crops. Puddling eliminates transmission pores through which gases would be exchanged in unpuddled soils. Cannell and Jackson (4) reviewed aeration stresses of crop plants. Without good drainage, there is limited oxygen for roots and soil organisms. Lack of oxygen restricts nutrient and water uptake and interferes with plant hormone formation and translocation. Plant growth is directly affected by microbial transformation of nutrients, formation of phytotoxic substances, and chemical reduction of nutrients.

An important objective of rice-based cropping systems research is to develop methods to reverse these soil conditions for 3-8 mo/yr without lessening rice yields.

Tillage can overcome the problem, but there are also other methods. Crop species, and cultivars within species, have different abilities to cope with inhospitable root environments (Table 3). Another strategy is to create a well-aggregated plow layer with high organic matter content that is easily converted to an aerobic soil suitable for dryland crops after rice. This strategy is used in Japan, China, and Korea. Because percolation rates are high, abundant water may be necessary for the strategy to be practical.

Water tables and interflow

After rice is harvested and dry season begins, water tables recede. If the surface soil is not reduced, or persistent perched water tables do not develop, crop roots extend rapidly as the water table recedes (14). Stuff and Dale (24) estimated that 17% of the ETa of a maize crop grown in a silt loam was from shallow groundwater. The fraction was 27% during extended periods without precipitation.

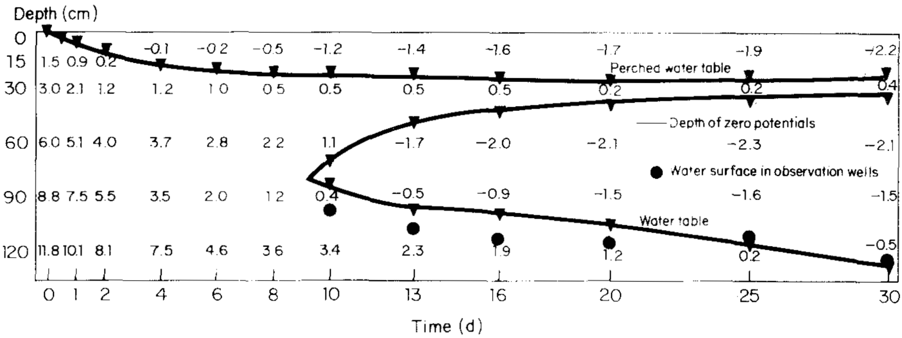
An evapotranspiration model that gives an index of excess moisture damage simultaneously with estimated ETa during the maize grain-filling period has been developed (16). An air-filled pore space of less than 12.5% is the criterion for excess moisture. The excess moisture index was weighted for crop age and fraction of the root zone with less than 12.5% air-filled porosity.

Perched water tables, like that in Figure 8, present difficult problems. Where water tables recede slowly or

Table 3. Shoot mass and root length and mass of 4 crops under controlled waterlogging (15).

Crop	Position[a]	Shoot mass (g)	Root length (cm)	Root mass (g)
Sorghum	H	1.9	15	0.27
	I	1.9	17	0.27
	L	1.7	12	0.20
Maize	H	2.9	19	0.46
	I	2.3	14	0.52
	L	1.9	15	0.31
Cowpea	H	2.9	19	0.30
	I	1.7	13	0.19
	L	1.2	11	0.13
Mungbean	H	1.9	19	0.19
	I	0.7	11	0.10
	L	0.3	9	0.11

[a]H = high, I = intermediate, L = low. Plants were grown on a slope, with standing water maintained at the lower edge of the slope to create a gradient of decreasing waterlogged root environments going up the slope.



8. Submergence (positive) and matric (negative) potentials during first phase drainage showing development of a perched water table. The perched water table, which formed above the B2tcn horizon, was detected after 9 d. Potentials were determined by tensiometers (18).

Table 4. Grain yield of crops grown in 3 terrace positions. IRRI, 1981-82.[a]

Terrace position	Grain yield (t/ha)			
	Rice	Sorghum[b]	Mungbean[b]	Mungbean[c]
High	1.9	1.5	0.87	0.68
Intermediate	2.5	1.6	0.52	0.71
Low	2.5	2.1	0[d]	0.20

[a] Rice means over 3 replications and 2 prior tillage treatments, means for other crops over 3 replications, and 3 planting or surface drainage treatments. [b]Planted after rice harvest on 9 and 16 Dec and 13 Jan in the high, intermediate, and low positions. [c]Planted on 19 and 20 Jul after early wet season rains. [d]Crop destroyed by powdery mildew.

perched water tables are persistent, the hazard of temporary excess moisture is present. It is greatest where soils are fine-textured or fields are low-lying. The water that may be available above a shallow water table may be both beneficial and hazardous to dryland crops.

Interflow creates problems for dryland crops similar to those from slowly receding ground water tables. Soil aeration is poor because water occupies the large pores. Interflow may be advantageous for rice. Table 4 shows the effects of terrace position on rice, sorghum, and mungbean yields. The upper position was 43 cm higher than the intermediate and 83 cm above the lowest. Crop selection and choice of planting date in relation to seasonal rainfall patterns are important when seepage-prone land is cultivated in sequence with rice.

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UNDERDRAINAGE OF LOWLAND RICE FIELDS

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Abstract

In clay lowland rice fields, rapid underdrainage is necessary for farm mechanization. However, underdrainage is difficult in fields with impervious clay subsoils. The first step is to dry the surface soil until it cracks. Leveling, making small shallow ditches in the field, allowing ample time for drainage, and backfilling the drain trench with highly permeable material are essential. Archival weather data can be used in simple drainage models to determine necessary bund height, precision of field leveling, and field drain spacing for optimum field drying rates.

UNDERDRAINAGE OF LOWLAND RICE FIELDS

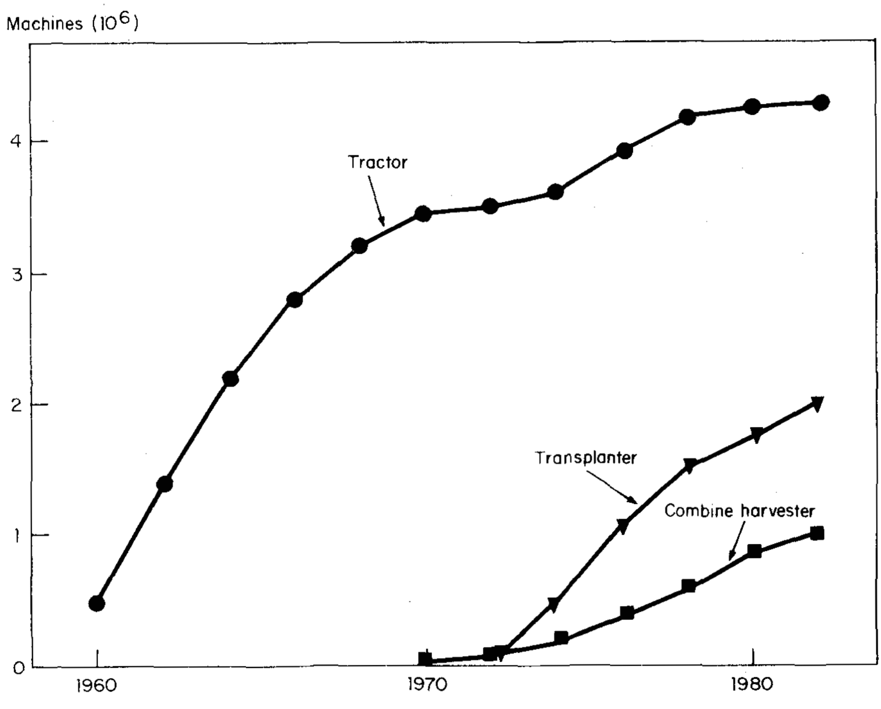
Farm mechanization began in Japan in 1960 (Fig. 1). However, large tractors and combine harvesters were difficult to use in poorly drained lowland clay rice fields in areas where monthly autumn precipitation exceeds 150 mm. Lowland rice fields must be drained for cultivation and harvest, and flooded during crop growth. At harvest, rapid drainage is necessary so fields can dry before combines enter.

Underdrains similar to those in upland fields were installed to improve drainage in the impervious clay soils (Table l), but were ineffective (Table 2) because water cannot percolate through to the drains.

Drainage in clay rice fields is complex and established drainage theory is not adequate to describe it. Field and soil characteristics should be examined carefully before installing underdrains.

LAYOUT AND STRUCTURE OF UNDERDRAINS

A typical Japanese rice field (6, 7) is 100 x 30 m (0.3 ha) (Fig. 2). There are an irrigation ditch and a road on one



1. Machines on Japanese rice farms, 1960-82.

Table 1. Characteristics of underdrains in lowland rice fields and upland fields.

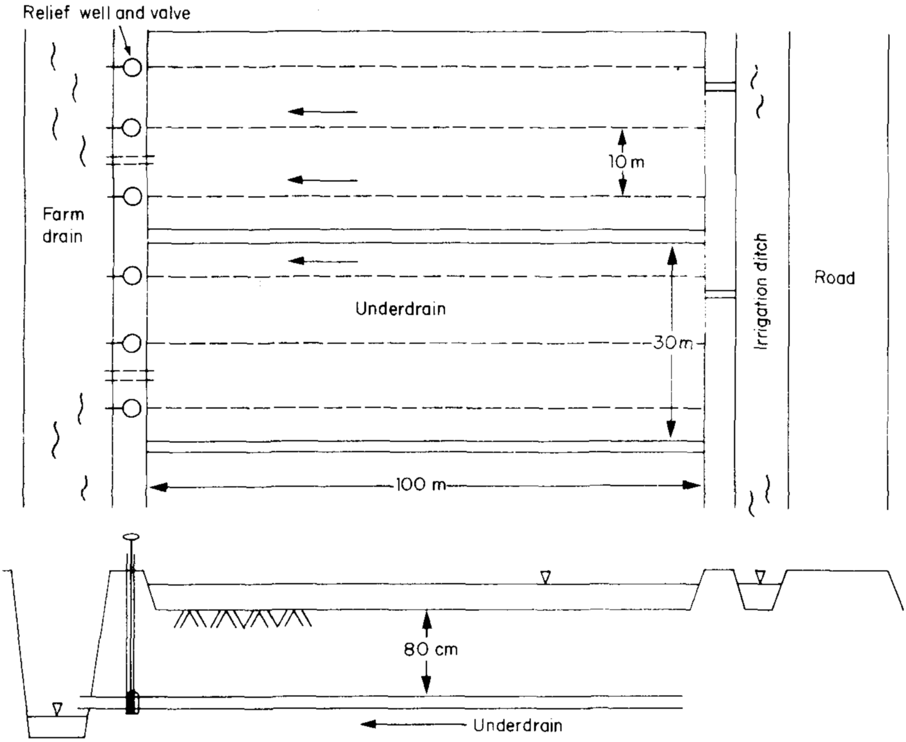
	Lowland rice field	Upland field
Purpose of drainage	To dry soil for mechanization	To lower ground-water level to promote better growth of nonaquatic plants
Period of drainage	Harvest and cultivation	All cropping season
Soil	Impervious layered soils, but made pervious by cracking Soil state changes seasonally	Pervious
Water flow	Through cracks of topsoil and backfilled underdrain trenches	Through all the soil
Relief wells	Yes	No

Table 2. Hydraulic conductivity of soils in clay lowland rice fields.

Soil layer	State	Magnitude of Ks (cm s^{-1})
Surface soil	Puddled	~ 10^{-5} - 10^{-7}
	Dried with cracks	~ 10^{-2} – 10^{-3}
Subsoil	Undisturbed	~ 10^{-5} - 10^{-7}
	Backfilled part	~ 10^{-2} - 10^{-3}

side, and a drain on the other. The underdrain pipes are plastic or tile and more than 5 cm in diameter. They run lengthwise, 80 cm below the soil surface at 10 m drain spacing. Each underdrain has a valve, called a suiko, at the farm drain. The suiko is closed when fields are irrigated, and opened for drainage.

If the pipes do not provide sufficient drainage, they are supplemented by mole drains. Mole channels are at 5 m spacing and oriented 90° to the direction of the pipes. This drainage system is called a combination drain. In certain ill–drained rice fields, groundwater flows up from the subsoil. Vertical drains are used in those fields.



2. Typical Japanese lowland rice field with an underdrain. Positioning of the underdrain is shown in the cross section (1).

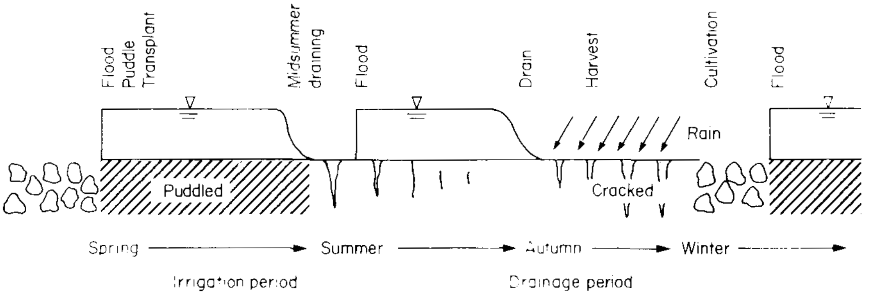
MANAGEMENT OF DRAINAGE IN CLAY LOWLAND RICE FIELDS

Soils in clay lowland rice fields comprise the topsoil (surface soil or cultivated soil), a hardpan, and the subsoil. Topsoil is 10 – 20cm thick and is regularly tilled (puddled, plowed). Puddling makes it impervious. When the topsoil dries, it becomes pervious as cracks develop.

The subsoil is almost impervious. But, with improved drainage, cracks that allow percolation gradually develop. However, it takes several years to dry and crack the subsoil.

Seasonal changes in topsoil

Seasonal changes in topsoil structure and moisture regime are shown in Figure 3. Rice fields are flooded with irrigation water in spring and topsoil is puddled, making it impervious. Fields are drained of surface water for about



3. Seasonal changes in surface conditions of clay lowland rice fields.

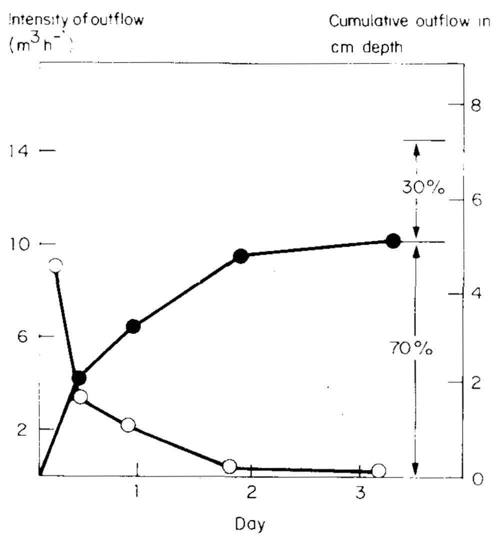
10 d in midsummer, then reflooded, and then drained again before the autumn harvest. If the field has effective surface-drainage and underdrainage, the topsoil dries and cracks and rainwater flows easily through the cracks to the drain pipes.

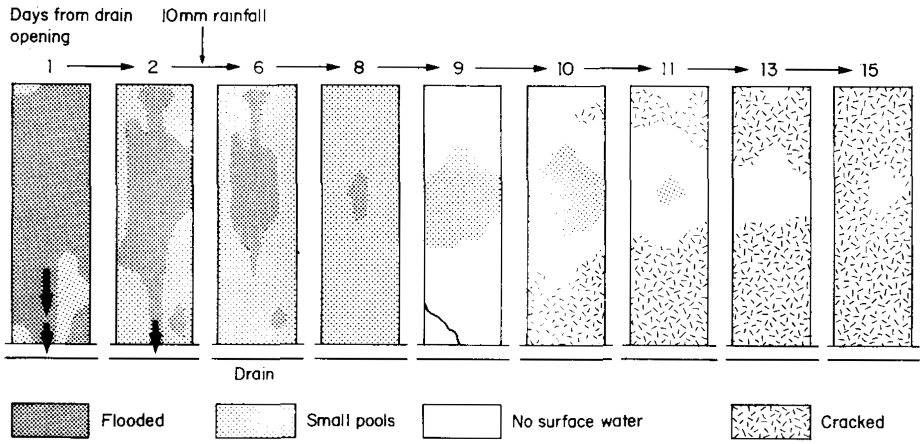
It is almost impossible to drain water through puddled, impervious topsoil. Therefore, surface drainage, which allows evapotranspiration to begin drying the topsoil, is the first drainage step.

Surface drainage

Observations on a sample field showed that when drains were opened, surface outflow continued for 2 d (Fig. 4), releas-ing 70% of the applied floodwater. The remaining 30% was

4. Surface outflow from a lowland rice field (1).



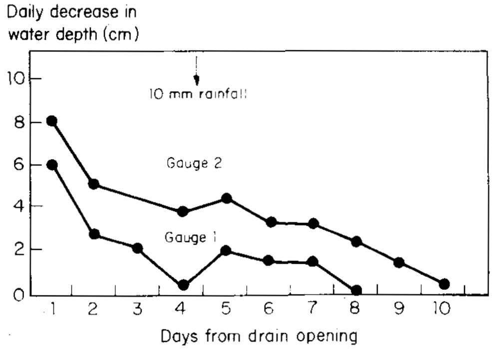


5. Surface water conditions of a clay lowland rice field during draining (2).

retained by the uneven field surface. Figure 5 shows progressive changes in surface water conditions of the rice field during this draining. Much of the field still was covered by standing water when the surface drains stopped flowing on day 2. Subsequently the water-covered area decreased and the area of cracked soil increased. However, substantial surface water persisted for 8 to 10 d and there were still small pools after 11 d (Fig. 5, 6). Only 10 mm of rain fell during those 11 d, which is much less than normal. Pools would have remained longer under normal rainfall.

Figure 6 shows the level of surface water decreased by no more than 4-7mm/d during the 11 d of draining. The rate of decrease may be ascribed to evapotranspiration, implying that percolation was almost zero.

Good surface drainage of clay fields is important. Draining should be started as early as possible, and fields



6. Daily decreases of surface water level in a flooded clay lowland rice field (2).

should be carefully leveled so water drains quickly. Additionally, drainage can be speeded by digging shallow ditches that lead to the surface drain.

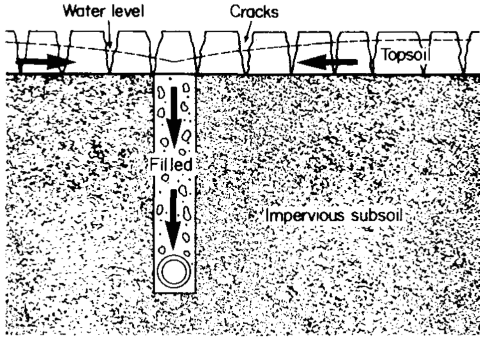
Underdrainage

Effectiveness of underdraining depends on leveling, drainage period, permeability of backfill, evaporation, and rainfall duration and intensity. A profile of a clay lowland rice field with underdrains is shown in Figure 7. Water flows horizontally, then vertically, through cracks in the topsoil and into the drain. To allow free water percolation, the composition of the fill in the drain trench is important. The trench must be backfilled with loose, dry soil. In Japan, rice husk instead of soil has been used as fill to obtain high permeability.

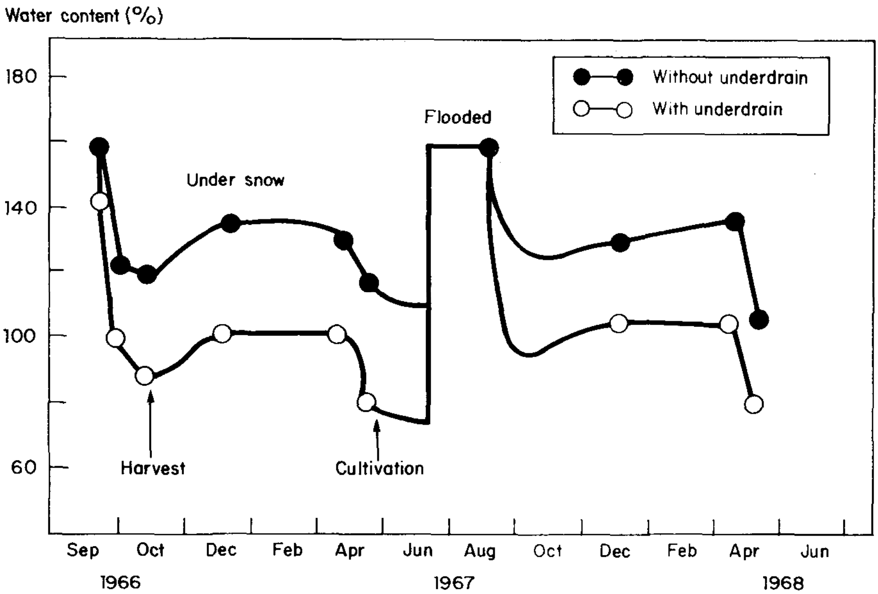
Underdrainage and trafficability

We studied the effect of underdrainage on rice fields in Niigata, a rainy area in central Japan. Rice fields with underdrains were surface-drained for 1 mo. Cracks in the soil developed at harvest, when water content was less than 100% of gravimetric value (Fig. 8). Rice fields without underdrains did not drain well. A tractor moved easily in fields with underdrains, but sank more than 20 cm in poorly drained fie1ds.

When drains were open for 1 wk only (Fig. 9), the soil did not crack and there was little drainage. Underdrains were similarly ineffective in poorly leveled fields.



7. Profile of a clay lowland rice field with underdrains.

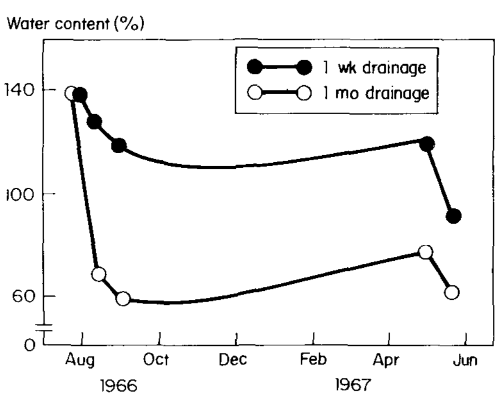


8. Effect of underdrainage on soil-water content of lowland rice fields in Niigata (3). Water content is represented as percentage fraction of gravimetric value for the topsoil layer.

A DRAINAGE MODEL

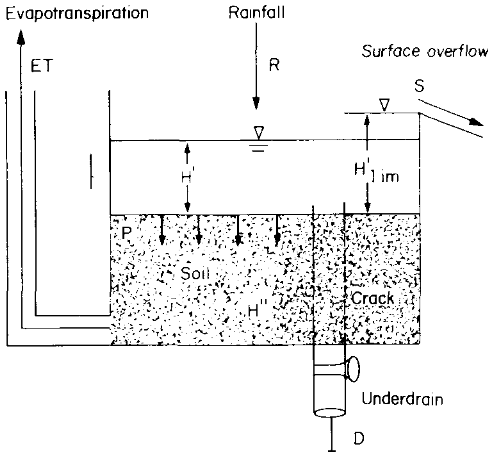
Calculating the water balance

Drain performance depends on several factors, especially rainfall duration and intensity, which differ annually. We developed a formula, based on a simple tank model (Fig. 10), to calculate drain performance and intensity of drying for clay rice fields.



9. Soil-water content of lowland rice fields as affected by drainage duration in Niigata (3). Water content is represented as a percentage fraction of volumetric field capacity value for the topsoil layer.

10. A drainage model for a clay lowland rice field (4).



H' is the depth of surface water; H" is the depth equivalent of the water content of surface soil; R, ET, P, S, and D are daily total rainfall, evapotranspiration, percolation into surface soil, surface overflow, and drain discharge. After S stops, water remains in the field to a depth of H'_{lim} which is influenced by bund height and by the unevenness of the field.

Water depth on the nth day is

$$H'_n = H'_{n-1} + R_n - P_n - D_n \qquad (H'_n < H'_{lim}) \qquad (1)$$

and D_n is nearly zero until cracks develop in the surface soil.

Water content of the surface soil is

$$H''_n = H''_{n-1} + P_n - ET_n \qquad (2)$$

and for $H'_n > 0$, with saturated soil, H''_n is constant so:

$$P_n = ET_n. \qquad (3)$$

When there is no water on the surface (H' = 0), soil–water content H" decreases. When H" decreases by 30 or 40 mm, the surface soil cracks and becomes pervious.

The influence of leveling, as manifest in H'_{lim}, wase-valuated using Eqs. l and 2 and data from Kashiwazaki dis–trict for 1957-67 and for a 1–modraining period. First, H'_{lim} was set to 10 mm, a value that corresponds to optimum leveling. Results (Fig. 11) show that soil dried thoroughly in all years but 1958 and 1964, when there was heavy rainfall. Conversely, for H'_{lim} set to 30 mm, fields dried well only in 1960, 1965, and 1966.

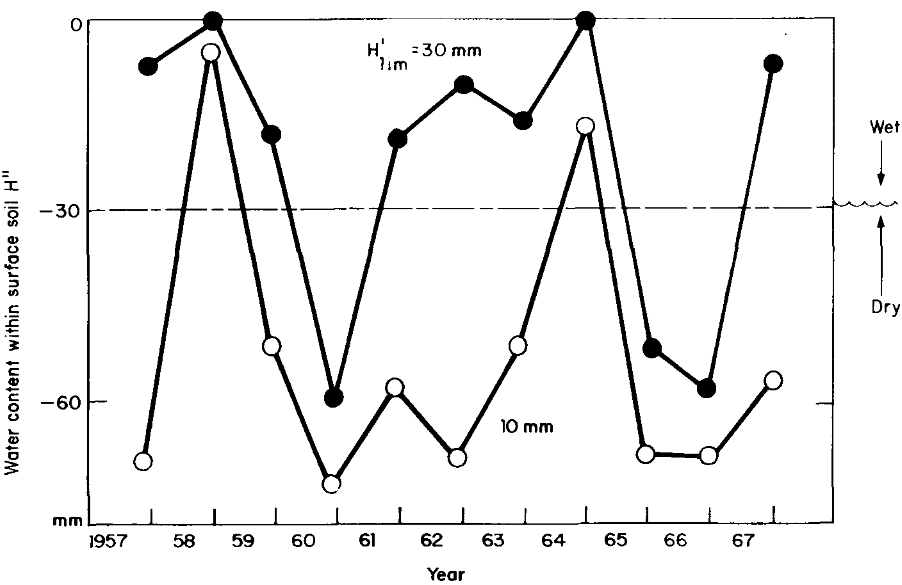
By using this rainfall-driven model, it is possible to calculate the effects on soil drying of such factors as draining period, leveling, and underdraining.

Mathematical analysis by Datcy's Law

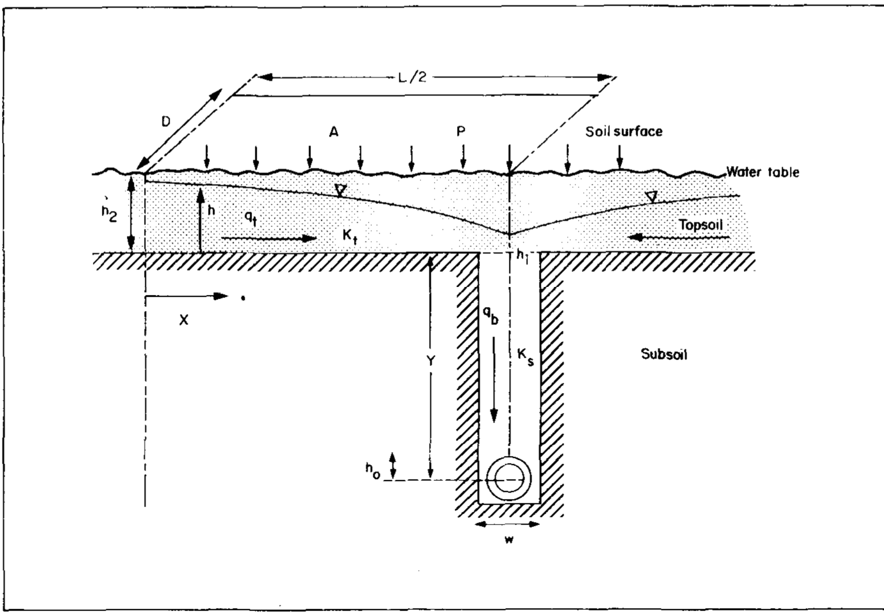
For saturated vertical flow through a backfilled underdrain trench (Fig. 12), where

L is drain spacing,
D is the length of the drained area,
w is the width of the backfilled trench,
K_s is the saturated hydraulic conductivity of backfilled parts,
K_t is the hydraulic conductivity of topsoil,

P is the percolation rate, and
q_t and q_b are the volume flow rates in the topsoil and the backfilled trench that derive from area A:



11. Calculated values of H" for 11 successive yr in the Kashiwazaki district with a l-mo draining period (4).



12. Flow analysis of a drained field by Darcy's Law. The one drain shown drains a total area twice that of A.

$$q_b = K_s Dw(Y + h_1 - h_0)/2Y \quad (4)$$

and noting that $(h_i - h_0) \ll Y$

then

$$q_b \doteq K_s Dw/2 \quad (5)$$

The drained area A is DL/2.

Unit area drainage discharge H_b is calculated as

$$H_b = q_b/A \doteq K_s w/L \quad (6)$$

If we use the values, $K_s = 0.01$ cm s^{-1} and w = 15 cm, then

$$H_b/\text{cm d}^{-1} \doteq 13{,}000/L \qquad \text{(L in cm)} \quad (7)$$

Hence for L = 10 m, we calculate H_b = 13 cm/d, or 130 mm/d, or 5 mm/h. This value of unit area drainage will thus be sufficient to drain rainfall of intensity up to 5 mm/h, and daily rainfall totals of 130 mm. For horizontal flow through the saturated topsoil, the equation of continuity gives

$$\eta D\frac{\partial h}{\partial t} = -\frac{\partial q_t}{\partial x} + \frac{PD}{864000} \tag{8}$$

where h is porosity and P is rainfall (mm/d). In a steady state, ¶h/¶t = 0,and applying Darcy's law

$$\frac{d}{dx}\left(-K_t hD\frac{dh}{dx}\right) = \frac{PD}{864000} \tag{9}$$

After integration and substitution of boundary conditions:

$$K_t(h^2 - h_1^2) + P(x^2 - L^2/4)/864000 = 0 \tag{10}$$

and noting that $h = h_2$ at $x = 0$:

$$(h_2^2 - h_1^2) = PL^2/3456000\ K_t. \tag{11}$$

If we assume $h_1^2 << h_2^1$, then:

$$h_2 = h_{max} = (L/1859)\sqrt{P/K_t} \quad \text{(cm)} \tag{12}$$

For the values L = 10 m, K_t = 0.01 cm/s, and P = 10 mm/d, we obtain h_{max} = 17 cm. For a value so high, surface soil would not dry. It may therefore be concluded that drain spacing should be reduced. If the spacing is reduced to 5 m, as is usually done in high rainfall areas, then Eq. 12 determines h_{max} as 8.5 cm.

This drainage model has necessarily involved many simplifications. There has for example been no allowance for nonuniform and time-varying hydraulic conductivity of the topsoil, nor for varying rainfall intensity. Consequently, the model's predictions may not be sufficiently accurate for drainage scheme design. Thus, before designing and installing underdrains in previously undrained fields, performance should be evaluated for similar drains in fields with comparable soil and water conditions.

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MINERALOGY AND SURFACE PROPERTIES OF THE CLAY FRACTION AFFECTING SOIL BEHAVIOR AND MANAGEMENT

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ABSTRACT

The mineral composition of the clay fraction is discussed in terms of crystal structure and of chemical and physical properties related to mineralogy. The main transformation processes affecting the clay fraction and the conditions in which they occur are briefly described. Examples are given of relations between landscape position, dominant transformation process, and clay mineralogy. Differences between surfaces of clays and their bulk composition may develop naturally, as external conditions change, and through management. Although it generally is impractical to change the composition of the clay fraction, some changes in surface properties are feasible, These, may mask or alleviate undesirable characteristics of the clay fraction.

MINERALOGY AND SURFACE PROPERTIES OF THE CLAY FRACTION AFFECTING SOIL BEHAVIOR AND MANAGEMENT

Changing the fertility of a soil is relatively simple, although temporary. It is more difficult to change the physical or hydrological characteristics of a soil, although cultivation, drainage and irrigation, or mulching make desired changes for a season or longer.

The clay mineral composition of a soil generally cannot be economically changed within a human lifetime. The user must live with the mineralogy of the clay fraction.

In rare cases, rapid changes may occur in the clay fraction of soils. For example, halloysite, a crystalline clay mineral, may form in an amorphous clay fraction within a few years if the soil periodically dries. This happens in young volcanic soils when arable crops replace a rainforest.

In 1934, Edelman (14) hypothesized that the clay fraction of soils could consist of mixed gels containing Si, Al and bases, and crystalline layer silicates of different kinds, and that the clay fraction could be formed from weathering products of the primary minerals in coarser fractions. He also postulated that crystalline clays could consist of complicated mixed crystals: both as mixed-layer structures and as solid solutions containing a range of major and trace constituents.

This balanced, modern view contrasts with views that neglect structure or base contents, and consider the clay fraction to consist of an inorganic, colloidal, hypothetical soil acid (termed pyrophyllic acid because of its similarity in composition to pyrophyllite).

We need to consider the crystalline nature of the bulk of the clay fraction in many soils, the presence of amorphous or x-ray amorphous material that may determine surface properties of the clay fractions, and the important, rapid changes that may occur in the surface of the clay fraction, although most of the material may remain substantially unchanged in composition or structure.

Dixon and Weed (12) have compiled an excellent survey of available information on the clay fractions of soils.

MINERAL COMPOSITION OF THE CLAY FRACTION

The properties of a soil are largely determined by the proportion and the nature of the clay fraction. In most soils, the clay fraction consists of

- layer silicates (clay minerals in the strict sense);

- crystalline minerals such as quartz, anatase, or palygorskite (a Mg–Al silicate with a fibrous structure);
- Fe and, sometimes, Al oxides and hydroxides, which may be crystalline or amorphous;
- amorphous or paracrystalline aluminosilicates (allophane, imogolite); and
- organic compounds associated with the mineral part of the clay fraction.

Some properties of the mineral materials are summarized in Table 1.

Most plains soils contain a combination of clay minerals. Upland soils tend to have a simpler clay mineralogy. In either case, one or a few clay minerals may dominate the soil properties.

There are two broad groups of clay minerals: a group with permanent charge that have a moderate or high cation exchange capacity (CEC) at all pH values of interest, and a group with pH–dependent charge.

Clay minerals with permanent charge

Clay minerals with permanent charge have layers consisting of two tetrahedral sheets (mainly silica) enclosing an octa–

Table 1. Some chemical and physical properties of soils with clay fractions dominated by different materials.

Dominant material in clay fraction or on surface	Properties[a]				
	CEC	K or NH_4 fixation	Phosphate fixation	Swell-shrink ratio	Physical stability
Vermiculite	Very high	High	-	Moderate	Moderate
Beidellite	High	High	-	High	Moderate
Montmorillonite, nontronite	High	-	-	High	Moderate
Illite	Moderate	Low	-	Moderate	Moderate
Kaolinite, halloysite	Low*	-	High	-	Low
Allophane, imogolite	Very high*	-	Very high	Moderate/ low	Moderate**
Fe, Al oxides, and hydroxides	Very low*	-	High,Very high		High
Al-interlayered clays	Low*	-	High	Moderate/-	Moderate

[a] *pH-dependent. - not significant. **high against rainfall or water erosion; allophane soils low under load.

hedral sheet (mainly A1 or Mg oxide). Substitution of A1 or Fe(III) for Si in the tetrahedral sheets, or of Mg, K, or Fe(II) for A1 in the octahedral sheet causes the permanent charge. Swelling clay minerals or smectites such as montmorillonite, beidellite, and nontronite are examples of clay minerals with permanent charge.

The exchangeable cations that compensate the permanent charge are electrostatically bound to the clay surfaces. Some of them, A1 in particular, are closely attached to the surface. The remainder are in a diffuse layer. There are few anions within this layer near the clay surface because of electrostatic repulsion, and water molecules near the clay surface are firmly oriented by the electric field. The diffuse layer is thin where the exchangeable cations are largely trivalent (Al) and divalent (Ca, Mg), and where the soil solution is concentrated. With increasing dilution, or an increasing proportion of monovalent cations (Na), the diffuse layer thickens.

Such clays can contain much water in their diffuse layers that is unavailable to plants. In the smectite clay soils of the Sudan Gezira, for example, moisture depletion by plants stops at about 25 mass percent, while soil saturation is at about 36 mass percent (17). Although water can be transported through the diffuse layers, albeit slowly, salts cannot because of the exclusion of anions from them (33). This process, called salt sieving, reduces efficiency of salt removal from saline heavy clay soils. Salt concentration is lower in drainage water than in the soil solution.

This is not the only reason for relatively low efficiency of salt removal from clays with high CEC. Most swelling clay soils are structured, with peds surrounded by cracks from shrinkage. Many also have tubular pores caused by biotic activity. As Bouma and coworkers showed in several studies (6), part of the irrigation water applied to a structured clay soil flows through the large voids without removing more than a small fraction of the salt within the peds. This is called bypass flow. If soluble plant nutrients are applied to the soil surface in such a system, part of them will be carried below the rooting zone by rain or irrigation water. This water will move through large voids, and the nutrients will make insufficient contact with cation exchange sites within the soil structure.

The salt-sieving effect can be minimized, but not avoided, by keeping the salt concentration high for as long as possible and by increasing the proportion of divalent and trivalent cations. Bypass flow can be minimized or eliminated by avoiding water saturation of large pores, e.g. by applying low rates of irrigation water or by puddling the surfacehorizon.

Swelling clay soils may become virtually impervious through water saturation, for example under lowland rice, or through excessive or frequent irrigation. Shrinkage by drying generally restores the structure of the surface horizon and the hydraulic conductivity of the subsoil horizons by forming an intersecting system of cracks. This is useful for dryland crops after lowland rice. In soils with high shrink–swell ratios, bulk density probably does not limit root penetration (24), as it does in other soils.

On slopes in water–saturated conditions, soils with mainly smectite are subject to slow creep of the surface material or sudden deep slumping along a rotational plane (22).

Swelling clay minerals have a moderate proportion of substituted atoms, hence a relatively low charge density. Therefore, the exchangeable cations are bound only moderately strongly, and spread out in a diffuse layer. Each layer of the clay structure contributes to CEC and swelling characteristics.

Other clay minerals with a similar structure, such as illite and vermiculite, have much higher proportions of substitution, hence a high charge density. These minerals bind certain cations with enough energy to fix them between adjacent layers in nonexchangeable form. Particularly ions such as K, which fit neatly in holes in the clay structure, produce a rigid stack of clay layers. Only the outer surfaces and, to a varying extent, imperfectly fitting layers within the stacked structure, then contribute to cation exchange. These clay minerals swell and shrink much less thansmectites.

On the one hand, they contain much K within their structure, which during weathering becomes slowly available to plants. On the other hand, parts of the clay structure that are depleted of K can very readily fix fertilizer K (5, 13) when it is present at temporarily high concentration. Because the ammonium ion is physically very similar to K, NH_4^+ also can be fixed by vermiculite or K–depletedillite (1), but somewhat less strongly. At least some of it appears to be available to lowland rice (25). One swelling clay mineral, beidellite, has a structure in which NH_4^+ fits particularly well. Soils containing beidellite fix ammonium and K very strongly (2).

Clay minerals with pH-dependent charge

Clay minerals with variable charge have layers of alternating tetrahedral silica and octahedral A1 hydroxide sheets and very little substitution charge. Kaolinite and halloysite are primary examples. Kaolinite normally occurs as hexagon-shaped or rounded flakes about 1 µm in diameter that are much coarser than swelling clay minerals. Halloysite occurs in a hydrated form with water layers between clay layers and in a dehydrated form that is similar to, but less well ordered than kaolinite. Halloysite often occurs as curved or rolled plates (tubular) or as globular aggregates and is much finer than most kaolinites.

The A1 at the edge of the sheets is positively charged, particularly at low pH, and produces a small anion exchange capacity. Chloride and nitrate ions are exchangeable on such sites, but phosphate and silica are bound tightly and remain fixed (11, 30). Kaolinites generally have relatively coarse particles, which causes fixation to be small. Fine-grained kaolinites, and halloysites — which are extremely fine-grained with large edge areas, can fix large amounts of applied phosphate (3).

Clay minerals of pH-dependent charge have very low CEC that increases with pH through dissociation of OH groups. Changes in water content cause almost no swelling or shrinking. Soils dominated by kaolinite or halloysite generally have no or only weak ped structure. Jones (24) estimated that root penetration in those soils is impeded above a critical bulk density, given by (1.2 + 0.005 x sand %).

Soils on steep slopes with a clay fraction with small water holding capacity, for example, mainly kaolinite or dehydrated halloysite, do not creep or slump, but may form debris avalanches in very wet conditions where bedding planes of the rock run parallel to the slope (22).

When soils dominated by kaolinite or halloysite become dense after land clearing, through rain impact, or by wheel or bullock traffic or plow pressure during cultivation, they do not regain their structure and hydraulic conductivity by wetting and drying like swelling clay soils, but need to be biologically or mechanically restored. Restoration may be accomplished by mulching to stimulate worm activity, or by ripping or cultivator treatment if the soil is not too moist. The same problem occurs where such soils are puddled for lowland rice and subsequently used for a dryland crop. Vierhout (36) gives procedures for safe management of such soils.

Al–interlayered materials

In certain soils containing clay minerals with permanent charge, the interlayer spaces of the clay minerals are blocked by sheets of partly neutralized A1 ions. These incomplete and generally poorly ordered sheets consist of ring structures such as $Al_6(OH)_{15}^{3+}$. They are not exchangeable, neutralize a considerable part of the CEC, and restrict swelling. Fairl'y complete A1 interlayers thus convert clays with permanent charge into materials similar to kaolinite.

Even moderate A1 interlayering greatly affects clay stability against dispersion, as experimentally verified by Muranyi and Bruggenwert (31). At low salt concentrations, an illite material dispersed and collapsed into a virtually impermeable mass at an exchangeable sodium percentage (ESP) of about 30 and above. The partly Al–interlayered material was permeable at all ESP values tested up to 80.

This may be relevant to reclaiming sodic or saline–sodic soils. Acid formed after applying S or finely ground pyrite, as in parts of India, or waste acid from chemical industries, as used locally in the U.S.S.R., presumably dissolves some A1 from clay minerals besides Ca from lime that way be present. This produces A1 interlayers and dissolved calcium sulfate, both of which aid reclamation.

Fe(III) and A1 oxides and hydroxides

Soils with low–activity clays (clay fractions with low CEC) often contain gibbsite [$Al(OH)_3$] as well as kaolinite, generally as discrete clay–sized particles. Gibbsite aggravates the management problems because its CEC and moisture–holding capacity are essentially zero and because applied phosphate is fixed more severely by gibbsite than by kaolinite.

Fe(III) oxides also may occur in the clay fraction as discrete, crystalline particles of goethite or hematite. They generally have relatively low specific surface and properties similar to gibbsite, at least in well–drained soils.

Fe oxides or hydroxides also form generally discontinuous coatings on kaolinite and other clay minerals. They often are amorphous, have a very high specific surface, and drastically modify the charge and physical properties of such soils. CEC is very low. Phosphate fixation is severe and remains so except after very large phosphate applications. Structural stability is much higher than in kaolinitic soils with low proportions of Fe oxides. Infiltration rates remain high even after compaction by rainfall, and traffic does not readily collapse pores.

In surface soils with high organic matter content, the association of organic matter and Fe oxides to some extent counteracts all these effects. Wetland conditions also modify the effects of the finely distributed Fe(III) hydroxides. Reduction of Fe(III) phosphates increases phosphate availability. Reduction of Fe(III) oxides to Fe(II) increases CEC directly and there is an additional indirect increase because of the associated rise in pH.

Amorphous aluminosilicates

Amorphous aluminosilicates and related materials that have only short-range order include allophane and imogolite. These occur in many young volcanic soils. Such soils have very high moisture retention and phosphate fixation and low to very high pH-dependent CEC. They may have very high organic matter content that is presumably protected against rapid microbial decomposition by association with large amounts of A1.

These soils are quite stable against rain impact and are not erodible, but may fail under load. Failure may occur as landslides, slumps, or creep (36). Soils with amorphous clay constituents and hydrated halloysite may turn liquid, and slow-moving earthflow over considerable depth may occur frequently, even where slopes are not steep (22).

All the kinds of failure mentioned for clays occur when soils are water-saturated. Preventing failure on a sloping or steep landscape with wetland terraces depends on drainage at the bottom of the terrace walls and, where possible, on careful terrace construction, with the least permeable material near the surface. These techniques were raised to the level of a fine art by the Ifugaos of Banaue, Philippines (29).

ORIGINS OF THE CLAY FRACTION: TRANSFORMATION PROCESSES

The clay fraction in soils may be transported and deposited, along with other fractions of the sediment; it may be inherited from a weathered sedimentary rock; or it may have been formed by weathering of minerals in coarser fractions, or transformed from other clay minerals.

On young land surfaces, such as recent alluvial plains or slopes with moderate or high erosion, the nature of the clay fraction is largely determined by the original material. Because many sediments have a wide source area, their clay fractions are a mixture of, for example, illite, montmorillonite or vermiculite with or without some A1 interlayering, kaolinite, and some clay-sized quartz. The mixture tends to be constant within an alluvial plain but may vary from one river plain or estuary to another.

On older land surfaces, for example on river or coastal terraces or in uplands with little erosion, weathering and clay transformation are more important. A few major clay transformation processes, acting on a variety of original materials, can explain the different clay mineralogies that occur. The processes, discussed by Brinkman (8), are summarized below, in order of decreasing areal importance.

- Hydrolysis by water containing carbon dioxide, which removes silica and basic cations.
- Cheluviation, which dissolves and removes especially Al and Fe by chelating organic acids.
- Ferrolysis, a cyclic process of clay transformation and dissolution influenced by alternating Fe reduction and oxidation, which lowers CEC by Al interlayering.
- Dissolution by strong mineral acids, which attack all clay minerals, producing acid Al salts and amorphous silica.
- Clay transformation under neutral to strongly alkaline conditions (reverse weathering), which creates minerals such as montmorillonite, or in extreme cases palygorskite or analcime.

Hydrolysis by water containing carbon dioxide

Hydrolysis by water containing carbon dioxide, also called desilication, and sometimes weathering, is a dominant process of clay formation and transformation, particularly in the humid tropics, and also in part of the temperate zone.

Water in equilibrium with atmospheric carbon dioxide has a pH about 5.6, the same as uncontaminated rain water. When excess rain water passes through a soil, clay minerals begin to dissolve congruently (proportionately) until the solubility product of gibbsite, $Al(OH)_3$, is reached. This happens at an Al concentration of about 1 nmol/litre at pH 5.5-6. Thereafter, gibbsite precipitates, while clay minerals continue to dissolve and silica is removed by percolating water. Thus, gibbsite is formed in, for example, kaolinitic soils under perhumid conditions.

Where leaching is less rapid and the clay fraction contains minerals such as montmorillonite or illite, which contain a high proportion of silica and basic cations, continued dissolution increases silica concentration to above about 100 nmol/litre. Then, kaolinite is stable over gibbsite. Kaolinite may form from, for example, montmorillonite or feldspars under humid conditions. In both cases, any Fe that is released from the mineral structure precipitates as hydroxide or as goethite (Fe00H) because of its extremely low solubility.

Where concentrations of Mg or other structural cations are relatively high during weathering, montmorillonite or vermiculite may change into their Al-interlayered equivalents because these are stable over kaolinite and gibbsite under those conditions. Even when kaolinite is stable over Al-interlayered material, the latter may still be formed as an intermediate step in the transformation sequence.

The stability relationships discussed here are based on thermodynamics, but can be visualized most simply in terms of solubility products that determine whether a given compound dissolves or precipitates.

Hydrolysis of clay minerals (or of feldspars or other weatherable minerals in coarser fractions) is slow. Silica is removed by percolating water in concentrations of about 1 to 10 mg/litre, and basic cations in similar or lower concentrations.

Where K concentrations in solution are kept very low by plant uptake, dissolution of K from illite may proceed faster than desilication of the material. Then, illite may change to K-depleted (swelling) illite, and with further minor changes into vermiculite or a swelling clay mineral similar to beidellite. These, in turn, would be subject to the slower transformations previously discussed.

Decomposition by strong acids

When pyritic clays, which occur in many mangrove areas, are oxidized by drainage, sulfuric acid forms. The acid rapidly dissolves clay minerals, at pH between 2.5 and 3.5, until silica concentration is about 2 mmol/litre (about 120 mg/litre). Then, amorphous silica precipitates.

If Mg and K concentrations are high enough, for example in saline conditions, montmorillonite and illite may be stable with respect to kaolinite. Then, the direction of clay transformation is away from kaolinite, in contrast to hydrolysis.

Dissolution by strong acids results in A1 concentrations ranging from 1 to several hundred mg/litre, which is several orders of magnitude higher than in hydrolysis by water with carbon dioxide, and to silica concentrations of about 100 mg/litre, about 10 times higher (34). The process can therefore proceed much faster than hydrolysis if the reaction products are removed, as for example in drainage water.

Reaction products that are not removed may form amorphous silica and A1 interlayers in swelling clay minerals when pH rises to about 5 or higher.

Cheluviation

During cheluviation, organic acids specifically dissolve A1 and Fe and remove them as chelates. The direction of clay transformation is similar to that during dissolution by strong acids, but no A1 interlayers form.

Ferrolysis

Clay decomposition and transformation by ferrolysis require two alternating sets of circumstances. In water-saturated conditions with some leaching, the soil is reduced and pH rises slowly as $Fe(OH)_3$ changes to Fe^{2+}, which becomes exchangeable and soluble. Leaching removes part of the exchangeable base cations. Water saturation alternates with drying and oxygen entry. Then, exchangeable Fe^{2+} oxidizes, producing $Fe(OH)_3$ and exchangeable h. The latter attacks the clay minerals, as do other strong acids, but the A1 and other cations released from the clay structure become exchangeable, not soluble. The silica from the clay may remain as unsupported edges of the former clay structure.

During the next period of water saturation, Fe(III) hydroxides are again reduced to Fe^{2+}, part of which displaces exchangeable A1 and other cations into the soil solution. Part of the silica in the unsupported edges also dissolves. Leaching may remove some silica, bicarbonate, and part of the A1 and other cations.

Because pH rises during reduction, the remaining A1 is partly neutralized, and polymerizes into ring structures such as $Al_6(OH)_{15}^{3+}$. These form incomplete octahedral sheets in the interlayer spaces of swelling clay minerals. Such A1 interlayers are not exchangeable. They neutralize part of the CEC, and block other, originally exchangeable, cations in inaccessible cavities of the incomplete layer structure.

Ferrolysis thus creates Al-interlayered materials with low CEC, formed from swelling clay minerals with originally high CEC, and also amorphous silica -- the latter in contrast to hydrolysis by water containing carbon dioxide. The rate of clay transformation by ferrolysis is probably an order of magnitude higher than that of hydrolysis by water with carbon dioxide.

Clay transformation under alkaline conditions

Where concentrations of silica and structural cations are relatively high, mineral synthesis rather than dissolution can occur. This process sometimes is called reverse weathering.

In alkaline or neutral conditions with moderate Mg concentrations in solution, montmorillonite is stable over clay minerals such as kaolinite and vermiculite. Montmorillonite forms in plains or valleys in humid to semiarid tropical climates, with enough Mg and silica inflow from adjoining uplands.

Where Mg concentrations are high, as in some semiarid and arid environments, a fibrous mineral, palygorskite, forms that contains more Mg than montmorillonite.

In strongly alkaline conditions with high Na concentrations in solution, analcime forms, generally in a clay fraction dominated by montmorillonite. Because the Na in the structure of this mineral is partially exchangeable, such soils have anomalously high exchangeable sodium percentages.

CLAY MINERALOGY AND LANDSCAPE POSITION

Different clay transformation processes tend to dominate in different climates: desilication in perhumid climates, reverse weathering in arid conditions, or ferrolysis on level sites in climates with strongly constrasting wet and dry seasons. In many climates, however, soils on crests or slopes have clay mineralogy very different from that in the valleys or plains -- not because of different parent materials but because the soil hydrology produces different clay transformation processes, even over short distances.

The relations between landform, hydrology, soil forming processes, and clay mineralogy of lowland rice soils were summarized by Moormann and van Breemen (29).

Kaolinite and smectite

Red or brown kaolinitic soils on upland slopes alternate with black smectite clay soils in valleys or plains over large areas in humid to semiarid Africa and Asia. The upland soils, formed by hydrolysis by water containing carbon dioxide, are strongly to weakly acid with low or moderate base saturation, and have a mainly kaolinite clay fraction, often some illite, and Fe(III) oxides, quartz, and feldspar. The CEC of the clay fraction is uniformly low.

The valley soils were formed by clay transformation under neutral or alkaline conditions, with silica and base cations leached from the uplands. The surface horizons of these soils may have a clay fraction containing smectite, with kaolinite and illite transported from the uplands. The deeper horizons have mainly smectite. Smectitic valley soils generally are base saturated, tend to have neutral pH, and have high CEC.

Mohr (28) described an early example of such a soil association in a mountain landscape on Java. An analyzed example (19) from West Africa is the Shepeteri toposequence. Management aspects of upland Alfisols and valley Vertisols of the Deccan Plateau were studied by Krantz et a1 (26). In the Deccan Plateau, however, the soil differences are at least partly due to very different parent materials (granitic and basalt-derived, respectively), not only to landscape position and hydrology.

Al-interlayered and interstratified minerals

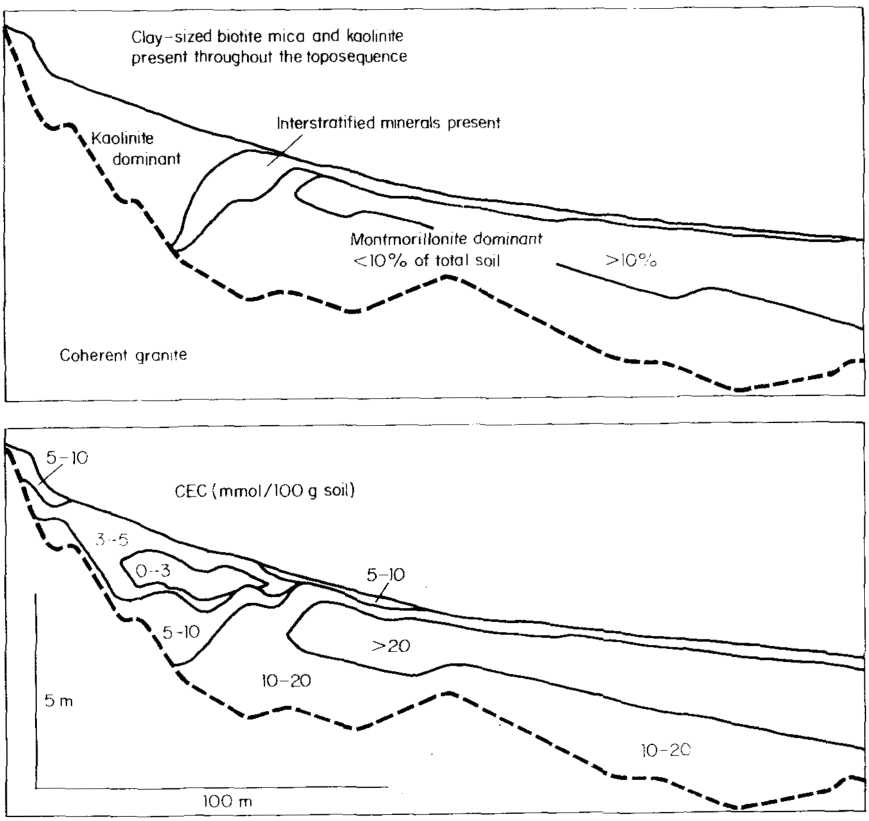
Where slopes are more gentle and soils on lower slopes are periodically water-saturated, Planosols (e.g. Albaqualfs), or less extreme surface-water gley soils, may be found between upland and valley soils.

Such soils may have Al-interlayered material in the clay fraction, or interstratified minerals: these may have the same general structure as smectite but show incomplete swelling because of A1 interlayering of part of the material. These periodically wet soils, which are subject to leaching rather than the accumulation that occurs in valleys, have low clay content and low CEC in the clay fraction of upper horizons. They generally are more acid than well-drained soils on steeper or higher parts of the landscape.

Ferrolysis presumably is the main process that has formed the seasonally wet soils on gentle slopes and low rises, as opposed to hydrolysis on uplands and clay formation under neutral or alkaline conditions in valleys or depressions.

Two such toposequences were studied by Bocquier (4). One extends from granitic upland through a gentle slope into a nearly level plain (Fig. 1). The other appears to be virtually flat, but in fact has elevation differences up to 1 m and slopes up to 1%. Even these have been enough to cause major soil and clay mineral differences.

In flatter landscapes, for example, the older river plains and low terrace landforms of Bangladesh (7), seasonally wet soils with low clay content in surface horizons and Al-interlayered clay fractions cover most of the landscape. Perennially wet, heavy clay soils without evidence of clay destruction, occur in the depressions.



1. Mineralogy of the clay fraction and CEC (mmol/100 g soil) in the Kosselili toposequence, Chad. Generalized from Bocquier (4).

Amorphous clay minerals

In areas with recent volcanic activity, particularly on tuff, soil forms rapidly because of the large proportion of easily weatherable material. Initially, this material supports high silica and base cation concentrations even during intensive leaching. If pH also is high, smectite forms. High runoff on steep slopes may decrease the leaching rate, and extend this stage.

Allophane forms rapidly from dissolved silica and polymeric octahedral Al compounds, presumably at somewhat lower pH and lower base cation concentrations than does montmorillonite. After continued leaching removes most of the base cations and readily dissolved silica, their concentrations in the soil solution become so low that kaolinite or halloysite is stable over montmorillonite. Amorphous aluminosilicates tend to crystallize and form imogolite, then halloysite, and eventually kaolinite, with the effects of time being aided by those of periodic drying.

In a well-drained toposequence on basic volcanic rocks in a perhumid climate, from near the crater of Quoin Hill, Sabah to the bottom of the slope, Eswaran and Sys (15, 16) showed a toposequence trend. There were major proportions of allophane or related amorphous material in the clay fraction on the steep upper slope. These gradually decreased to zero in the oldest soils on the more gentle downhill slope. Smectite predominated on the upper slope, and decreased to near zero at midslope. Kaolinite and halloysite increased from minor proportions upslope to dominate in the oldest downhill soils.

A similar toposequence can be found from Mount Makiling to Los Baños, Philippines. The highest part of the slope has typical Andisols, with mainly amorphous materials in the clay fraction. A lahar (a former mudflow) of the same origin constitutes the upper part of the IRRI farm. It has soils similar to the midslope soil at Quoin Hill, but the adjacent plain where the lower part of the IRRI farm is located, which contains materials of the same origin, has imperfectly drained swelling clay soils -- presumably the result of clay transformation under high silica and basic cation concentrations in drainage water from the adjacent upland.

SURFACE VERSUS BULK COMPOSITION OF CLAY FRACTIONS

The mineral composition of a clay fraction generally results from long-term processes and does not change quickly with a change in circumstances. However, the surface properties of particles in the clay fraction are not necessarily in equilibrium with the bulk composition. Surface properties change relatively quickly when external circumstances change, and surface rather than bulk properties are generally of primary importance for fertility, toxicity, and other physical and chemical aspects of soil management. Herbillon (20) summarized the nature and properties of clay and oxide surfaces.

Iron oxides

Soils with kaolinitic clay fractions containing less than about 12% Fe_2O_3 generally have the properties associated with kaolinite: low, pH-dependent CEC, moderate phosphate buffering capacity and fixation, low structural stability with consequent erodibility, and tendency to become dense when mechanically disturbed by traffic or rain impact.

In kaolinitic soils with more than 12% free Fe oxides in the clay fraction, the clay tends to have an oxide surface. Such soils have very low CEC, high structural stability and generally severe phosphate fixation. The percentage quoted varies depending on the nature and distribution of the oxides.

In smectite soils, too, there is a major distinction in structural stability and in degree to which a granular or fine blocky surface structure can be restored by drying. The Chromic Vertisols, with relatively high free Fe oxide content, have favorable properties in this regard, while at least some Pellic Vertisols do not. There may be other causative factors beside the content and distribution of Fe oxides.

Other substances or bonding agents

Structural stability in some soils may be due to surface features of the clay fraction besides organic matter, oxidic surfaces, or polyvalent exchangeable cations. In Australia, stabilizing features identified by Butler et a1 (9) included finely dispersed Fe oxides and also a fine clay fraction strongly bonded or cemented into silt-sized aggregates, probably mainly at the edges of clay packets rather than on planar faces. Silica cementation in these soils is possible but not proven. Intergrowth of clay mineral crystals may also be a factor, as may the large electrostatic interaction between clay layers of high charge density.

Anomalously high structural stability in certain Oxisols may result from kaolinite corrosion and subsequent cementation (10, 21).

In clay fractions of Kenyan soils with amorphous material, Wielemaker (37) found indications that CEC at a given pH is higher with even minor increases in the ratios of extractable amorphous Si to A1 and Si to Fe. He also modified the charge characteristics experimentally by applying amorphous silica. Similar amorphous silica-Fe compounds with some Al, cover the surfaces of crystalline clay minerals in clay soils over large areas in Quebec and Ontario, Canada. These soils are very stiff in place, but may become virtually liquid when extensively sheared (27), even though the content of amorphous material is only 10-12%.

Rapid changes in surface properties

The most rapid changes in surface properties and physical chemistry of soils are caused by alternating reduction and oxidation. Reduction processes were extensively dealt with by Ponnamperuma (32).

During reduction, Fe(III) oxides change into soluble and exchangeable Fe^{2+}, with a concurrent rise in pH. In neutral soils with smectite or vermiculite in the clay fraction, this may cause synthesis of materials with a structure similar to smectite and containing Fe(II) in the octahedral sheet. Where such soils are perennially wet, Zn tends to be fixed in a form unavailable to lowland rice: perhaps because it can be built into the octahedral positions in the synthesized material. Upon reoxidation, Zn is again available, which suggests that the material is stable only in reduced conditions -- presumably because of its high Fe(II) content.

In acid soils, particularly those with kaolinitic clay minerals, soluble Fe^{2+} concentrations tend to rise to high levels because of low CEC and because conditions are unfavorable for precipitation of Fe(II) oxides or carbonates or for synthesis of silicates. Then, Fe toxicity may be observed in lowland rice, depending on the Fe^{2+} concentration in relation to the concentrations of nutrient cations and phosphate availability.

When a reduced soil is oxidized, Fe^{2+} changes into $Fe(OH)_3$. The original Fe oxides are thus distributed differently, and with a generally higher specific surface and activity. In high-activity clay soils, this may increase the stability of a structure established before inundation, as in flood-fallowing of sugarcane land in the Guyana coastal plain, or of a structure established just before oxidation, as in land preparation for wheat after rice in the Jangtze

Delta, China. In low–activity clay soils, the effects of alternate reduction and oxidation are less clearly beneficial, partly because leaching of nutrient cations tends to accelerate in periodically reduced conditions.

In soils with high amounts of active Fe or Al, for example with amorphous, halloysitic or oxidic clay fractions, phosphate fixation is severe and CEC may be low or very low. Phosphate or silica on the surface of such materials drastically changes their properties. Although very high phosphate applications to decrease or eliminate phosphate fixation may not be economic in most cases, they are effective and rapid. Using silica or finely ground silicates may be more economic, and also tends to lower the severity of phosphate fixation and raises CEC at a given pH. Substances that could be tried include wollastonite (Ca silicate), used as a silica fertilizer in some lowland rice areas, or ground feldspar, or basic slag, which contains phosphate and silicate.

In practice, Ca silicate applications on a Gibbsihumox in Hawaii gave disappointing results, but the high P–fixing capacity in Oxisols was reduced by long–termirrigation with water containing 30 mg Si/litre (18). This tripled water–soluble Si from 1.6 to 5.3 mg/litre, increased poorly crystalline soil Si from 730 to 1,360 mg/kg, and reduced P sorption (at 0.2 mg/litre solution concentration) from 235 to 100 mg/kg, compared with the soil that received low–Si irrigation water.

Jepson et al (23) showed that Si reacts with a gibbsite [$Al(OH)_3$] surface in quantities from less than a monolayer at pH 4 to rather more at pH 9, with an increase in CEC and decreases in anion exchange capacity and Al solubility at a given pH.

These findings can probably be summarized in the hypothesis that silication of oxidic surfaces is feasible, but that the process is much slower in the field than in the laboratory. It may be that in the field there is imperfect mixing and slow diffusion of silica to oxidic surfaces -- and the process may need several crop seasons for its completion.

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INFLUENCE OF SALINITY AND ALKALINITY ON PROPERTIES AND MANAGEMENT OF RICELANDS

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Abstract

There are millions of hectares of salt–affected soils on otherwise productive land on all continents and in many climates and landlords. There are two main groups of salt–affected soils: saline and alkaline. Saline soils have excess neutral soluble salts. Alkaline soils have high exchangeable sodium and high pH from sodium carbonate.

Rice often is planted during reclamation of both soils and is grown extensively on them in favorable climates although high salinity or sodicity may be a major constraint.

Although rice is not tolerant of high salinity, lowland rice culture with standing surface water significantly reduces salinity in the root zone through leaching 2nd dilution. Rice grows satisfactorily when electrical conductivity of the saturated paste extract from upper soil layers is 20 dS/m. It tolerates high sodicity and is an excellent reclamation crop that under good management yields well.

INFLUENCE OF SALINITY AND ALKALINITY ON PROPERTIES AND MANAGEMENT OF RICELANDS

Excess soluble salts reduce the productivity of several million hectares of otherwise productive lands. There are salt-affected soils on all continents and in many climates and landforms. Climate, landform, and physical and chemical characteristics of saline and alkaline soils determine their use, management options, and potential productivity. Rice is a popular crop for reclaiming salt-affected soils and is grown extensively where climate is favorable even though high salinity may be a constraint. This paper describes the influence of excess salts on properties and management of soils where rice is grown.

CLASSIFICATION OF SALT-AFFECTED SOILS

The physical and chemical properties of salt-affected soils and their effect on plant growth vary substantially. Salt-affected soils are generally categorized as saline or alkaline, depending on the salts, soil characteristics, and their effect on plant growth (3).

Characteristics of saline soils

Saline soils have high levels of neutral soluble salts such as chlorides and sulfates of sodium, magnesium, and calcium. If the electrical conductivity of a saturated soil extract is 4 dS/m, the soil is generally characterized as saline. Most saline soils have a much higher salt concentration.

At high soil salinity levels, sodium chloride usually is the dominant salt, but most saline soils have ample calcium salts for crop nutrition. Small quantities of boron and other toxic elements also may be present in the soil solution. The saturated paste pH of saline soils is nearly always less than 8.2, many have pH less than 7.0, and some are extremely acidic (e.g. acid-sulfate soils) (Table 1).

Saline soils generally have physical properties that favor plant growth. Because of excess neutral salts, they are well aggregated, with hydraulic conductivity equal to or higher than that of similar, nonsaline soils.

Plant growth in saline soils is adversely affected by low soil-water availability because of the soil solution's high osmotic pressure. Toxic concentrations of specific ions

Table 1. Characteristics of typical salt-affected soils (Bhargava, personal communication).

Depth (cm)	Mechanical composition (%)				pH	ECe (dS m^{-1})	Composition of saturation extract (meq/litre)					Sodium adsorption ratio
	Organic matter	Clay (<2 μ)	Silt (2-50 μm)	Sand (50 μm-2 mm)			Na^+	$(Ca+Mg)^{++}$	Cl^-	SO_4^{--}	CO_3^{--}	
					Coastal saline soil, Canning, West Bengal							
0-12	0.4	34	26	40	7.2	27	156	149	213	16	Nil	18
12-28	0.3	45	38	17	7.5	7	38	28	57	8	Nil	10
28-80	0.3	46	38	16	7.5	7	43	36	73	9	Nil	10
80-105	0.3	40	44	17	6.7	8	48	32	75	9	Nil	12
					Inland saline soil, Nayabans, Haryana							
0-11	0.8	10	19	71	7.2	78	692	612	1360	75	Nil	34
11-29	0.7	15	29	56	7.9	14	88	84	173	17	Nil	14
29-68	0.6	18	34	48	7.8	11	72	60	85	16	Nil	13
68-93	0.5	16	29	56	7.9	10	70	60	88	28	Nil	13
					Alkaline soil, Karnal, Haryana							
0-5	0.3	22	35	43	10.3 [a]	8.2	85	0.4	13	6	67 [b]	97 [c]
5-24	0.3	29	38	33	10.3	8.0	84	0.4	15	6	68	94
24-56	0.2	33	36	31	9.8	1.9	18	0.6	6	3	12	90
56-85	0.2	31	40	26	9.8	1.4	14	0.5	3	2	10	85

[a] pH measured in 1:2 soil-water suspension. [b] Represents CO_3^{--} + HCO_3^-. [c] Exchangeable sodium percentage values.

also may accumulate. Although the response of rice to excess salts has not been studied in detail, specific ion concentrations are likely to have adverse effects on yield when rice is grown in submerged fields.

Rice and saline soils

The management of rice in saline soils is situation specific. There are two saline landforms in India: coastal saline soils and inland saline soils.

Coastal saline soils. On 2.5 to 3.0 million ha of coastal soils on which rice is grown, salinity is a serious production constraint. Seawater intrusion through rivers, estuaries, and creeks and groundwater flow, tidal inundation, and wind spray are major sources of salt accumulation. Also, coastal areas are occasionally affected by cyclones with high tides that severely damage standing crops and may inundate vast areas.

Most coastal areas have high rainfall concentrated in June through September. Land is planted to one rice crop in wet season, and remains fallow the rest of the year. The groundwater table is high, usually 1–2 m below the soil surface in dry months, and at the surface in wet season.

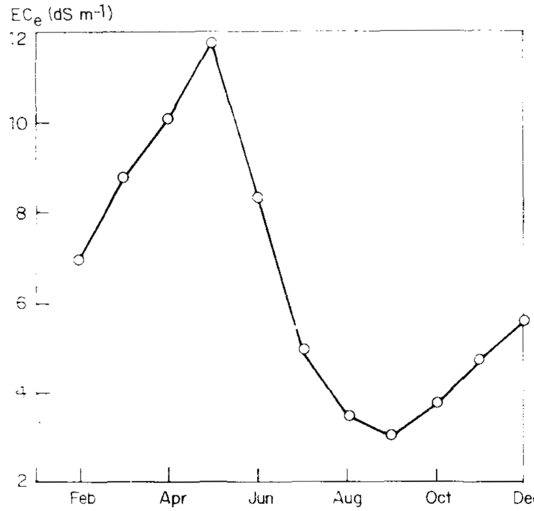
Groundwater salinity is high, varying from less than 4 dS/m in wet season to more than 20 dS/m in summer. Soil salinity varies seasonally and is highest in May. It decreases as wet season progresses and generally is lowest in September (Fig. 1).

Surface and subsurface drainage are impeded. Drainage of surface water is slow and difficult because of the concentration of rainfall, the flat topography, low infiltration rates, and the lack of a well-defineddrainage system. Deep submergence in wet season adversely affects rice growth, particularly of high yielding varieties.

Management to increase rice production includes construction of embankments with water control structures to prevent seawater intrusion and to allow rainwater to drain from fields. Bunds, surface drains, and farm ponds to store excess rainwater have been suggested to improve rice production (20).

In coastal areas, high soil salinity delays rice planting until rains have leached accumulated salts from the topsoil. Bandyopadhya and Sen (2) showed that kharif rice yield was significantly improved if chilies, cotton, or a second rice crop was grown during the preceding January to

1. Seasonal changes in salinity of the surface 15-cm soil in a typical saline soil. Cannlng, West Bengal.



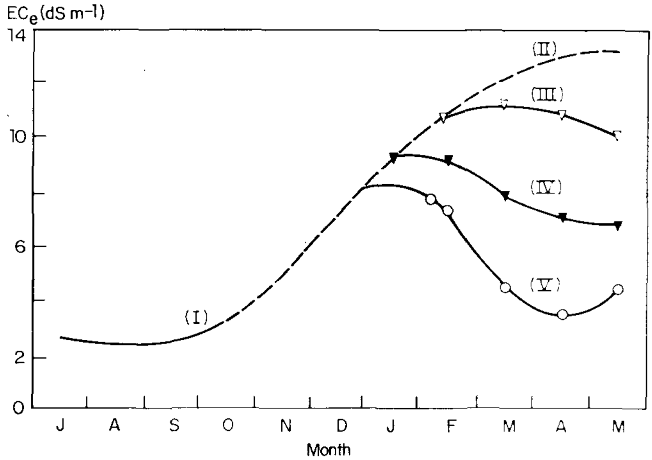
May (Table 2, Fig. 2). Nulching with 10 t rice husk/ha also reduced salinity and increased the yield of the following kharif rice crop.

Preliminary field studies (4) showed that 1.75–m–deep subsurface drains at 15- to 30–mspacing effectively lowered the water table, removed most soluble salts from the upper 60 cm soil layer, reduced salt accumulation after wet sea–son, and increased yields of the subsequent rice crop. However, installing subsurface grains is expensive and un–likely to be undertaken on a large scale.

Inland saline soils. Inland saline soils are common in irrigated arid and semiarid regions of India. Because irri-gation is expensive, rice, which uses water inefficiently, rarely is a recommended crop. Moreover, in many irrigation projects drainage is inadequate, and after several years the

Table 2. Grain yield of kharif rice as affected by land treatment during the preceding January to May.

Treatment	Grain yield (t ha^{-1})		
	Year 1	Year 2	Year 3
Fallow	3.6	4.9	3.0
Rice	3.6	5.7	4.0
Mulching with rice husk at 10 t ha^{-1}	4.4	5.3	4.1
LSD at P = 0.05	0.6	0.5	0.9



2. Changes in salinity status of the upper 15 cm of soil due to different cropping sequences: I – rice in kharif followed by fallow (II), chilles (III), cotton (IV), and rice (V) in the preceding January to May.

groundwater table rises, causing waterlogging and salinity. When other crops begin to fail, farmers often plant rice on such lands.

Without appropriate drainage, even rice yields poorly and in extreme cases nay not grow. With proper drainage, rice can be an important crop during reclamation of saline land.

Such reclamation involves leaching and draining the soils of soluble salts. Because water is limited in arid and semiarid areas, leaching fallow land seldom is justifiable; therefore rice is grown during reclamation.

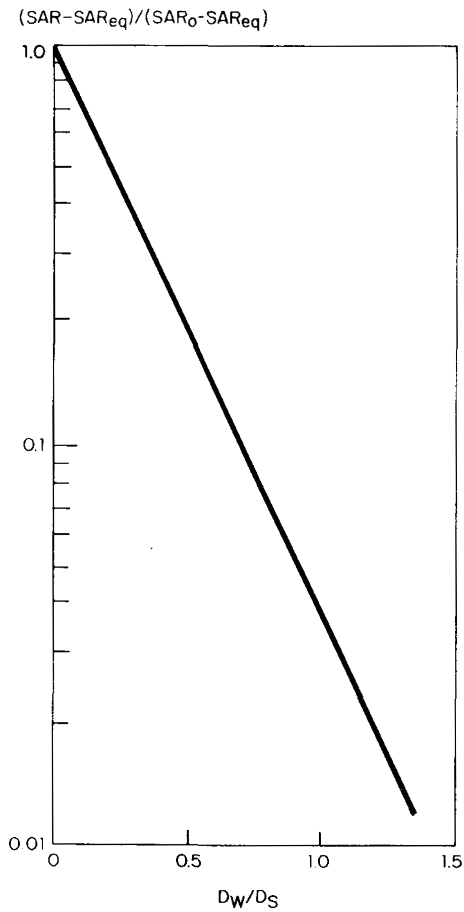
Rice does not tolerate excess salinity: at 6–7 dS/m salinity of the saturated soil paste extract, rice yield is halved (15). However, lowland rice culture with surface water throughout the growing season significantly reduces salinity in the rice root zone by leaching and diluting the salts. Rice has yielded satisfactorily even when electrical conductivity of the topsoil saturated paste extract was 20–25 dS/m (25). Table 3 shows changes in salinity in a heavy-textured, saline soil during three rice seasons (25).

It often is feared that if soils with high sodium adsorption ratio (SAR) are leached, then high sodicity will result. However, several studies (8, 13, 14) have shown that leaching highly saline, high-SAR soils tends to reduce salinity and sodicity (Fig. 3), but it may raise pH and lower permeability. These latter changes may increase rice yields.

Table 3. Changes in soil salinity during reclamation of a highly saline soil in Peru (25).

Depth (cm)	ECe[a] (dS m^{-1})				
	Initial	Before 1st rice crop	After 1st rice crop	After 2d rice crop	After 3d rice crop
0-1 0	169	34	20	17	12
10-20	130	45	22	16	12
20-40	75	54	32	21	16
40-60	42	47	33	26	21
60-80	34	42	35	29	23
80-100	30	41	36	30	24

[a] ECe = electrical conductivity of the surface soil extract. Rice yield was about 3 t ha^{-1} when electrical conductivity of the surface layers was around 20 dS m^{-1}.



3. Changes in SAR in relation to depth of leaching water per unit depth of soils, D_w/D_s is depth of leaching water per unit depth of soil, subscripts 0 and eq are initial and equilibrium values of SAR under existing soil-irrigation waterdrainage equilibrium conditions.

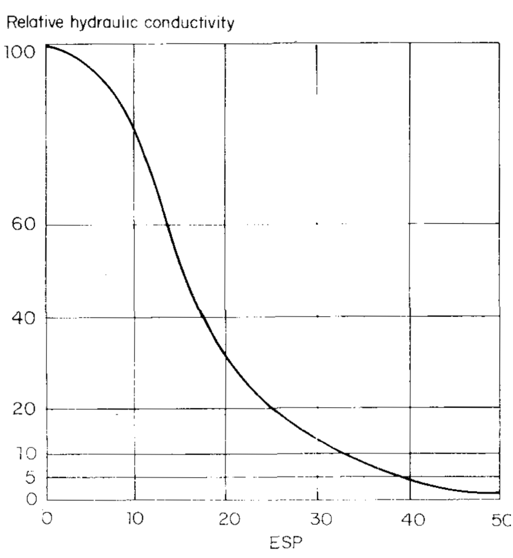
ALKALINE SOILS

Characteristics of alkaline soils

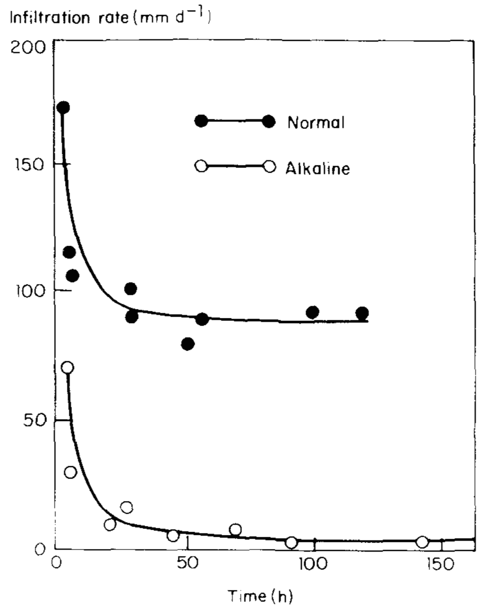
Soils with an exchangeable sodium percentage (ESP) of more than 15 are classified as alkaline. They generally lack neutral soluble salts, but contain substantial amounts of sodium carbonate. Their electrical conductivity varies, but often is less than 4 dS/m. Saturated soil paste pH is 8.2 or higher, and may be as high as 10.0. Studies (9) have shown that in alkaline soil, pH increases with ESP. Because high pH affects the whole range of physicochemical and surface soil properties (10, 11). its effects on plant growth are similarly mediated by several processes, of which sodicity is only one.

Excess exchangeable sodium (ES) and high pH strongly influence soil physical properties. As ES increases, soils become more dispersed and less permeable to air and water (Fig. 4). The extent of dispersion depends on particle size distribution, organic matter content, clay mineralogy, etc. Dispersion causes dense impermeable surface crusts that greatly reduce seedling emergence and water penetration. Figures 5 and 6 show changing infiltration rate and post-infiltration moisture content for a typical alkaline soil and an adjacent normal soil.

Excess ES and high pH also strongly influence the availability and transformation of essential plant nutrients. Toxic levels of sodium may reduce growth, or kill plants.



4. Schematic relationship between soil hydraulic conductivity and exchangeable sodium percentage (ESP).



5. Infiltration rate-time curve for an alkaline and a normal soil.

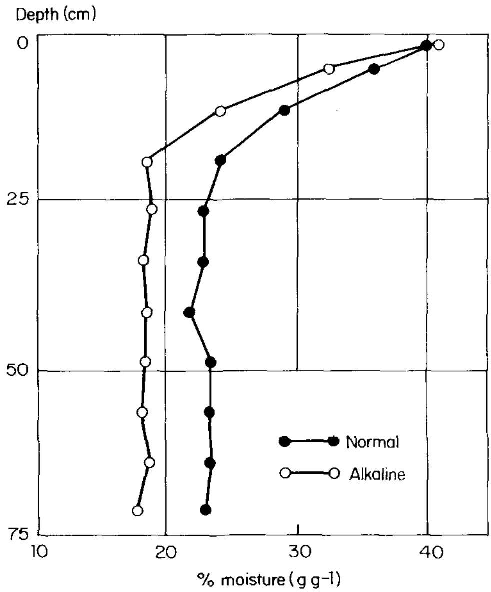
Alkaline soils and rice

In India, several million ha of alkaline soils in the Indo-Gangetic plains are on otherwise productive land. They have high sodium carbonate, ESP, and pH (Table 1). The soils almost always have calcium carbonate in varying quantities, and a calcic horizon at about 1-m depth. They are medium-textured with dominantly illitic minerals. Mean annual rainfall is 600 to 1000 mm. mostly from Jul to Sep. With supplemental irrigation, rainy season rice is the major crop and wheat is the post-rainy season crop.

Although soil amendments and leaching are necessary to reclaim alkaline soils, growing suitable crops during reclamation can reduce costs. Rice is an ideal crop to grow while reclaiming alkaline soils.

Tolerance of exchangeable sodium. Data in Table 4 and Figure 7 show the effect of different gypsum applications on ESP and rice and wheat yields. At ESP of about 50, rice yield was unaffected, but wheat almost died. For other crops, including legumes, yields are affected at ESP as low as 8-10.

Rice tolerates high ES because it grows well in standing water, and infiltration rates usually are sufficient to leach out toxic substances resulting from the reaction with



6. Postinfiltration moisture distribution in an alkaline and a normal soil.

ES of applied amendments. Also, rice has a shallow root system and so can grow well if sodicity is lessened in only the upper few centimetres of soil. Other crops need a deeper layer of low-ESP soil to yield satisfactorily.

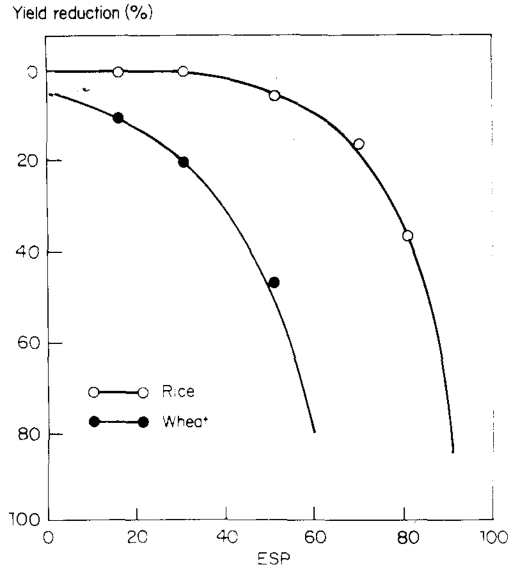
Although poor soil physical properties do not seem to affect rice growth adversely, excessive uptake of elemental sodium can be toxic at high ESP. Table 5 shows that weather and soil-moisture conditions influence sodium uptake. Tolerance of sodicity may thus depend on seasonal weather.

Table 4. Effect of gypsum on soil properties and yield of rice and wheat in a highly alkaline soil (26,27).

Gypsum applied ($t\ ha^{-1}$)	Infiltration rate ($mm\ d^{-1}$)		Exchangeable sodium percentage[a]		Grain yield ($t\ ha^{-1}$)	
	Initial leaching	During rice growth	0-15 cm	15-30 cm	Rice	Wheat
0	2	3	76	92	3.8	0.02
7.1	11	7	33	75	6.7	1.5
14.2	15	9	32	79	6.9	3.8
21.3	20	12	19	59	7.4	3.6
28.4	21	12	14	57	7.2	4.2
LSD at P = 0.05	4.6	1.8			0.6	0.6

[a]Determined on samples after harvest of the rice crop.

7. Fractional reduction of rice and wheat yields as affected by soil acidity (ESP).



Rice as a reclamation crop

In addition to tolerating sodicity, rice involves cultural practices that result in a decline in ESP during the growing season (Table 6). These practices facilitate the removal of ES by increasing the cross-sectional area of conducting pores and hence the permeability (16). Other studies (5) have shown that ES decreases when native insoluble calcium carbonate is mobilized by increased hydrolysis and carbon dioxide liberation by plant roots. Long term field studies (unpublished) showed that rice in a crop sequence gradually reduced sodicity. After about 10 yr, the top metre of soil was nearly free of sodium, although the whole profile was initially highly sodic.

Because 120-150 mm of rainwater can be stored on the surface of bunded rice fields, drainage needs are less and groundwater recharge is encouraged (17).

Table 5. Sodium content of 30-d-old rice seedlings in a wet and a relatively dry year as affected by gypsum application in a highly alkaline soil (4).

Gypsum applied ($t\ ha^{-1}$)	Na content (%)	
	Wet year	Dry year
0	1.6	2.3
5	1.1	2.1
10	0.8	1.8

Table 6. Effect of rice cultivation and gypsum application (ESP) (1).

Gypsum applied ($t\ ha^{-1}$)	ESP			
	Before rice		After rice	
	Depth/cm		Depth/cm	
	0-15	15-30	0-15	15-30
0	87	94	50	63
7.5	67	87	29	63
15.0	33	83	26	56
22.5	16	64	16	33
30.0	14	57	13	36

Nutrient management

High ESP and pH of alkaline soils affect the transformation and availability of several essential plant nutrients. Although rice tolerates high sodicity, special fertilizer management is necessary for optimum production.

Nitrogen. Alkali soils have low organic matter content and generally low available N. In laboratory studies, Rao and Batra (21) found that as much as 62% of urea-N applied to alkaline soil was lost through volatilization. Losses were only 30% in waterlogged (laboratory) soils.

Nitant and Bhumbla (18) reported that higher sodicity increased the time needed for nearly complete urea hydrolysis from about 3 d in soil with pH 8.6 to about 7 d for soil with pH 9.8. Several field studies have shown that rice grown in alkaline soils responds to higher levels of N application than rice grown in similar normal soils. There is thus a general recommendation that rates of N application for rice should be 25% higher for alkaline soils than for normal soils.

Phosphorus and potassium. Soils with high pH and high sodicity have high extractable P (7). Consequently, rice and wheat crops on some alkaline soils did not respond to applied P for 4-5 yr (6). K uptake for most crops, including rice, is less when sodicity is high (27); however, this effect has not been investigated thoroughly. Lack of crop response to K applied to some sodic soils was attributed to naturally occurring K-bearing minerals that supplied sufficient K for plant requirements (19).

Table 7. Effect of Zn on the yield and composition of rice grown in a gypsum-treated alkaline soil (22).

$ZnSO_4$ (kg ha^{-1})	Rice yield (kg ha^{-1})	Zn content (µg g^{-1}) At tillering	Grain	Straw
0	5.1	13.3	10.9	15.8
10	6.0	25.1	12.3	20.4
20	6.0	29.3	12.3	22.3
40	6.0	34.0	12.6	25.1
LSD at P = 0.05	0.6	5.6	0.9	2.1

Micronutrients. High pH, low organic matter content, and calcium carbonate strongly limit micronutrient availability to plants grown in alkaline soils. Zn deficiency is common and is accentuated by submergence and by gypsum application. Several field studies have shown that Zn application significantly increases rice yield. Singh and Abrol (22) showed that applying 10 kg $ZnSO_4$/ha eliminated Zn deficiency in rice grown on gypsum-treated, highly alkaline soil (Table 7).

Fe deficiency also reduces rice yields in alkaline soils. But applying Fe salts to correct the deficiency generally is not useful unless it is accompanied by prolonged submergence and organic matter amendments that change the soil oxidation status (12, 23, 24). Table 8 shows the effect of various amendments on extractable Fe and Mn in a highly alkaline soil after varying periods of submergence. These and other changes in sodic soils after submergence are

Table 8. Effect of submergence and amendments on extractable iron and manganese in a highly alkaline soil planted to rice (24).

Amendment	Submergence period[a] (d)	Extractable Fe (ppm) *b*	Extractable Fe (ppm) *c*	Extractable Mn (ppm) *b*	Extractable Mn (ppm) *c*
Control	0	3	14	2	12
	30	13	16	12	12
Gypsum, 12.5 t ha^{-1}	0	3	17	3	14
	30	15	21	15	16
Farmyard manure, 30 t ha^{-1}	0	3	60	3	63
	30	60	66	66	69

[a]Before planting rice, [b] = at planting, [c] = 30 d after planting.

reflected in the yield of rice grown in soils with varying sodicities (Table 9). Submergence was more beneficial in highly sodic soils.

Table 9. Effect of presubmergence on the yield of rice grown in soils of different sodicities (23).

Duration of subrnergence[a] (d)	Rice yield (t ha^{-1}) at ESP of				
	35	65	72	82	Mean
0	5.41	3.59	3.26	1.46	3.42
15	5.61	4.01	4.00	2.01	3.92
30	5.71	4.68	4.50	2.58	4.36
Mean	5.57	4.11	3.92	201	

LSD at P = 0.05. ESP = 0.16, submergence = 0.15, ESP × submergence = 0.30.

[a] Before planting.

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MORPHOLOGY OF LOWLAND SOILS AND FLOW OF WATER AND GASES

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ABSTRACT

Soil morphology can be used in two ways to characterize the flow of water and air through soils. Morphological features, such as mottling or cutans, indicate particular flow processes. Pore patterns allow quantitative characterization and prediction of these processes in heterogeneous soils.

In this paper, the various mottling features discussed may be used to extend interpretations beyond the usual consideration of chromas. Free-draining conditions are distinguished from those with very low hydraulic gradients.

Because mottling features are only indicators, soil physical and hydrological monitoring always is needed. Soil pores can be observed and measured to define optimal sample sizes for measurements in different soils. Using dyes to stain water-conducting pores adds essential morphological information and is described in four case studies. New field methods that use large, undisturbed soil samples are described, as are four studies that used morphological data for simulation models of water movement in biporous soils.

MORPHOLOGY OF LOWLAND SOILS AND FLOW OF WATER AND GASES

The relation between morphology of lowland soils and the transport of water, solutes, and gases can be studied in two ways: by physical interpretation of soil morphological features such as mottling and cutans, and by morphological observation and measurement of soil pores. Both methods can be used to define transport phenomena in field soils, which often have a wide range of pore sizes.

Physical interpretation of soil mottling has been used for many years, but more specific interpretations based on modern field measurement techniques are needed. Morphological pore measurements have been less used, probably because of limited interaction between soil physicists and morphologists. However, natural pore patterns must be considered when defining flow systems in heterogeneous, anisotropic field soils if measurements and simulation models are to be realistic. This paper discusses the two methods, with emphasis on morphological observation and pore measurement.

Flow of water and gases through soil is a dynamic process governed by physical laws with characteristic variables and parameters. Morphological features or pore patterns, such as large macropores, may suggest certain flow processes, but their actual occurrence can and should only be established by physical measurements.

Soil physical flow theory, as presented in many textbooks, assumes soils are isotropic and homogeneous. Few field soils are. Quantitative morphological data to characterize the true nature of soils are indispensable.

MORPHOLOGICAL FEATURES THAT INDICATE FLOW PROCESSES

Mottling phenomena

Mottling phenomena are widely used to indicate soil moisture regimes (6, 26, 30,). Mottling phenomena, defined by the USDA (28) in terms of colors with chromas of two or less, indicate reducing conditions. Reducing conditions are defined as corresponding to pressure heads more than -1 kPa (29).

There are two major mottled–flowsystems. Both reflect the flow of water and gases through soil. One has high hydraulic gradient, the other low. The flow processes are directly governed by natural precipitation or irrigation. Flow systems with high hydraulic gradient occur in two soil situations:

1.1 Soils with low saturated conductivity K_{sat} in the surface soil and a very deep water table or a permeable subsoil from which water drains rapidly.

1.2 Soils with a very deep water table or permeable subsoil with high K_{sat} in the surface soil that declines sharply when the soils desaturate. This is common in soils with continuous macropores.

Four subtypes occur in soils with low hydraulic gradient:

2.1 Soils with low K_{sat} and very low hydraulic gradients that do not cause significant lateral or vertical water movements. The soil becomes saturated with water that can be removed only by evapotranspiration.

2.2 Soils with high K_{sat} but with very low hydraulic gradients that do not cause significant lateral water movement. Water can be removed by evapotranspiration and there is some drainage.

2.3 Soils with low K_{sat} and low, but significant, hydraulic gradient where natural drainage and evapotranspiration lower the water table.

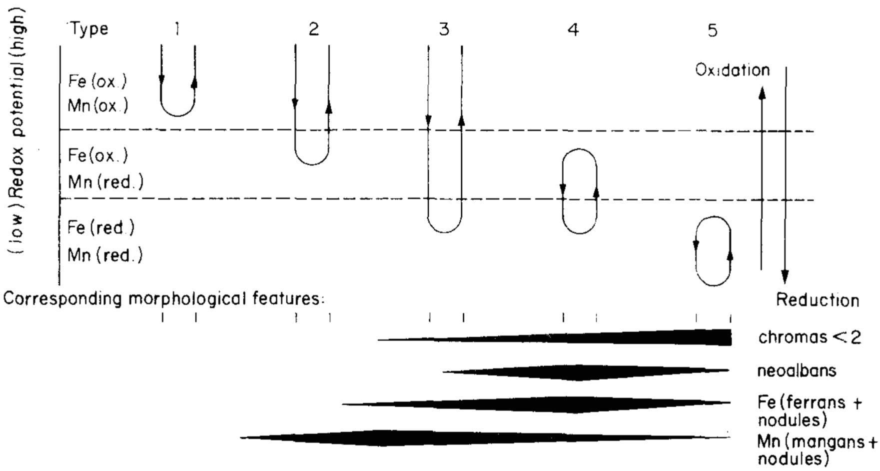
2.4 Soils with high K_{sat} and low but significant hydraulic gradient, where evapotranspiration, natural drainage, and possibly tile drainage lower the water table.

Type 1.1 is in surface water gleys or pseudogleys where water moves slowly down through a permeable soil horizon into an unsaturated subsoil where a deeper, real water table may occur (2, 26, 27). Type 2 flow systems are in groundwater gleys where the real water table, at zero pressure, forms the upper surface of the aquifer.

Visible mottling is formed by solution of Fe and Mn compounds during reduction (30). As redox potential decreases, Mn compounds reduce first, followed by Fe. The reverse occurs when a reduced solution containing both compounds oxidizes (Fig. 1 [4]).

The form of Fe and Mn concentrations after oxidation (Fig. 1) and the reduced color of the soil matrix can indicate annual water flow patterns, as illustrated by the following descriptions of flow systems.

In type 1.1. flow system, water input is higher than the K_{sat} of soil horizons in the upper part of the column. Mottling types 4 and 5 (Fig. 1) dominate. Reduced compounds are removed vertically or laterally and are likely to be oxi-



1. Schematic representation of redox regimes and associated soil moisture regimes and mottling features. red. = reduced, ox. = oxidized.

dized again in the unsaturated, aerated subsoil. Fe precipitates first.

Neoalbans are bleached zones around macropores that form when water infiltrates through the macropores into a relatively dry soil matrix when wet season begins. Organic matter from roots encourages reduction. Fe and Mn precipitation inside the still-aeratedpeds follows reduction (type 4, Fig. 1). Imposing this flow regime induced neoalbans in soil samples (31).

Later, complete saturation and reduction may occur inside the peds, causing low chromas in the soil matrix. Such chromas also can occur without macropore flow (type 5, Fig. 1). In this situation, mottling patterns indicate vertical flow through the horizon and lateral flow inside and between peds.

Type 1.2 flow system occurs in soils with continuous macropores where K drops sharply upon desaturation (Fig. 2). The crust test (10) allows distinction of these K curves.

Soils are saturated for short periods, but may be wet for extended periods (32). Wetness may reduce Mn compounds only, or it may also reduce Fe. Flow is lateral and toward air-filledmacropores. Mn and, sometimes, Fe coatings (mangans, ferrans) form on peds or along the walls of channels (mottling patterns 2 and 3, Fig. 1). Mangans were induced in soil samples by imposing this flow regime (33).

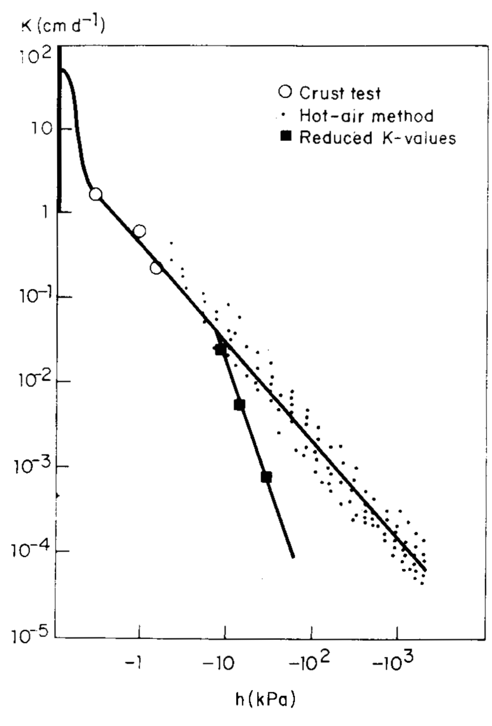
In type 2.1, reduced compounds are not removed by water flow. Mottling types 4 and 5 (Fig. 1) may occur, but they may be associated with more ferrans and mangans no ped faces than in 1.1. Ferrans and mangans form when the soil dries and precipitation occurs along larger air-filled voids.

Type 2.2 is here distinguished only to allow for removal of reduced compounds by artificial drainage, which is possible because of a relatively high K_{sat}. Drainage often is impossible in 1.1 systems.

Types 2.3 and 2.4 are intermediate-flow types, and include the possibility for enhanced removal of reduced compounds from the system.

Carefully describing soil profiles, including mottling features, helps understand complex flow processes. Such processes often are very difficult to characterize by random physical monitoring. However, mottling features cannot be used as conclusive diagnostic features to predict soil saturation or wetness. Some soils neither show mottling nor have relict mottles, and others inherently have low Fe and Mn content (24). Descriptions of mottling best serve when they comprise part of a broader physical and hydrological characterization.

Expanding traditional descriptions, which note only the occurrence of chromas of two or less (28), can significantly increase the value of mottling descriptions.



2. K-curve for a heavy clay showing sharp drop of K upon desaturation and a K_{macro} curve (see Fig. 5), for which 3 cubes of soil were tested.

Cutans

Cutans composed of clay, silt, and/or organic matter also indicate flow processes. They occur along the walls of water-conducting macropores and may indicate flows associated with deposition. The composition of the cutan indicates the associated flow regime (18).

In Alfisols, cutans of very fine clay develop along ped faces, indicating low water flow rates. Silt and even sand particles may be moved at higher flows, which may occur after intense rainfall. Cutan composition should be compared with soil material in overlying horizons to document possible displacement of soil materials within the profile.

DESCRIBING SOIL PORES FOR PHYSICAL FLOW MODELS

Although morphological features help predict flow processes, rigorous physical measurements are necessary. There is increasing use of soil morphology to define flow systems in field soils in terms of physical boundary conditions that are crucial in developing water-movementsimulation models.

The sand models of water flow, as defined in soil physical theory for isotropic, nonswelling, and homogeneous porous media, often are inadequate for anisotropic, swelling, heterogeneous field soils.

Flow systems in those soils may be characterized by defining pore patterns through morphological descriptions that distinguish macropores occurring between peds or as channels in a soil matrix with or without peds. Such characterizations also can be used to define representative elementary volumes for sampling purposes. This application of soil morphology is particularly useful because the data often could not have been otherwise obtained.

Observing and measuring soil pores

Various schemes have been proposed to describe soil pores (18). Pores can be described as planar voids (cracks), channels (made by soil fauna or roots), as single or compound packing voids between elementary soil particles or aggregates, and vughs. Vughs are irregularly shaped voids larger than the simple packing voids between elementary soil particles. Pores are described by type, size, shape, and arrangement, and by number of pores per unit surface area.

Much information can be gained by examining pore configurations of large, fresh soil samples in the field. Examining thin soil sections by microscope provides further data. However, relating pore configuration to the flow of water and gases through soil is difficult because flow processes depend on continuity of large pores, which is difficult to establish by examining a small soil sample.

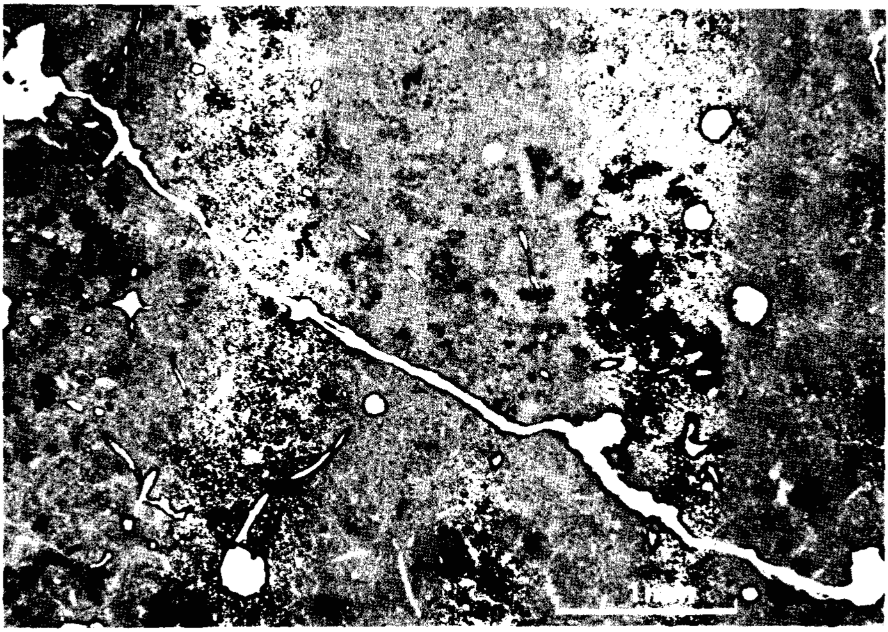
Except for sands, where all pores transport water and gases, most soils have biporous systems. Biporous soils have large pores, through which water and gases move, and small pores in the natural soil aggregates (peds) through which there is little gas or water movement.

Functional characterization

Morphological methods describe all pores, irrespective of their effect on flow processes. To determine specific pore flow processes, dyes such as methylene-blueand other chemical tracers have been used to stain the walls of water-conducting pores (1, 22, 25). Gypsum has been used to determine the volume of large pores in dry cracked clay soils (17). The following studies are examples of functional characterization of macropores (8).

Saturated flow in a heavy clay soil. Undisturbed samples of a clay soil that was nearly saturated for several months were percolated with a 0.1% solution of methylene-blue and water (15, 16). Horizontal slices of soil were freeze-dried. Thin sections of the slices were studied to establish pore-continuitypatterns (Fig. 3). Observations indicatedthat

1. K_{sat} was governed by small, 30-µm-diametepore necks. Slight changes in pore neck significantly affected K_{sat}. For example, a 22-µmpore neck gave a K_{sat} .of 50 mm/d, and a 30-µmpore neck gave 250mm/d.
2. Larger, water-conducting (stained) pores usually occupied less than 1% of the soil volume. Therefore, they should be described by number per unit area rather than by relative volume.
3. Flow occurred mainly along planar voids, contradicting the assumption for Dutch clay soils that swelling completely closes cracks.
4. K_{sat} of six different clay soils could be calculated from morphoiogical data (16).



3. Thin section image of a wet clay soil in which water-conducting, continuous planar voids are stained with methylene-blue.

4. Vertical ped face of a prism at 50-cm depth, showing blue bands that represent vertical infiltration (bypass flow) of water after sprinkler irrigation of a dry clay soil.

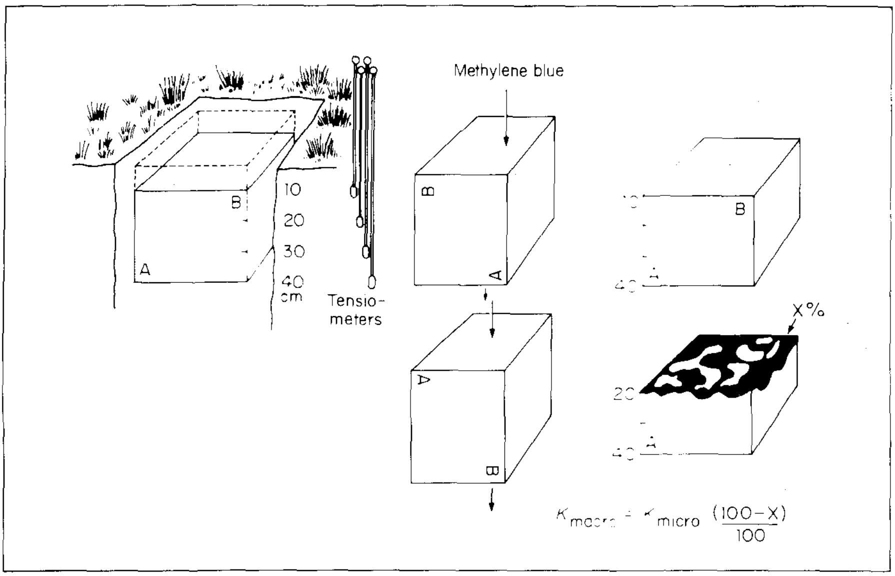
Infiltration of sprinkler irrigation in a dry clay soil. Vertical infiltration of free water through unsaturated soil horizons is called bypass flow. To determine bypass flow in a Dutch clay soil, five sprinkling intensities were imposed on four clay soils (11). Methylene-blue, in water, was sprinkled on cracked, dry clay soil in 1.0 x 0.5 m experimental plots. Soil was excavated from below the plots to observe infiltration patterns. These consisted of 5 to 7 mm wide vertical bands on the ped faces (Fig. 4). The number and surface area of bands were recorded at 10-cm increments to 100-cm depth.

The total (vertical) surface contact area S defines the area available for lateral infiltration into the dry peds. S increased up to 200 cm^2 as sprinkling intensity increased, but the stained fraction remained low. A coarse prismatic structure with peds of 10 cm cross section has an S of 20,000 cm^2 per 10 cm depth in a 0.5 m^2 plot. Therefore, the maximum stained S of 200 cm^2 represents only 1% of available vertical surface of infiltration.

Effects of horizontal cracking on upward, unsaturated flow. As vertical cracks may cause bypass flow, so soil shrinkage also may cause horizontal cracks that impede upward water flow in unsaturated soil (14). The following method was devised to stain air-filled horizontal cracks at different moisture contents and corresponding negative pressures.

A 30-cm cube was carved from the soil (Fig. 5), encased in gypsum, and turned on its side. On the turned cube, the gypsum seal was cut away from the upper and lower surfaces, and the sidewalls were kept sealed. A solution of methylene-blue and water was poured into the cube to stain the air-filled cracks. The surface area of the stained cracks was determined after returning the cube to its upright position. A separate cube was used for each (negative) pressure.

The K-curve for the peds (Fig. 2) is normalized for each pressure sampled. When, for example, 50% of the horizontal cross sectional area is stained, K_{unsat} for upward flow is 50% that of K_{unsat} at the same pressure in the peds. The normalized K-curve is termed K_{macro}.



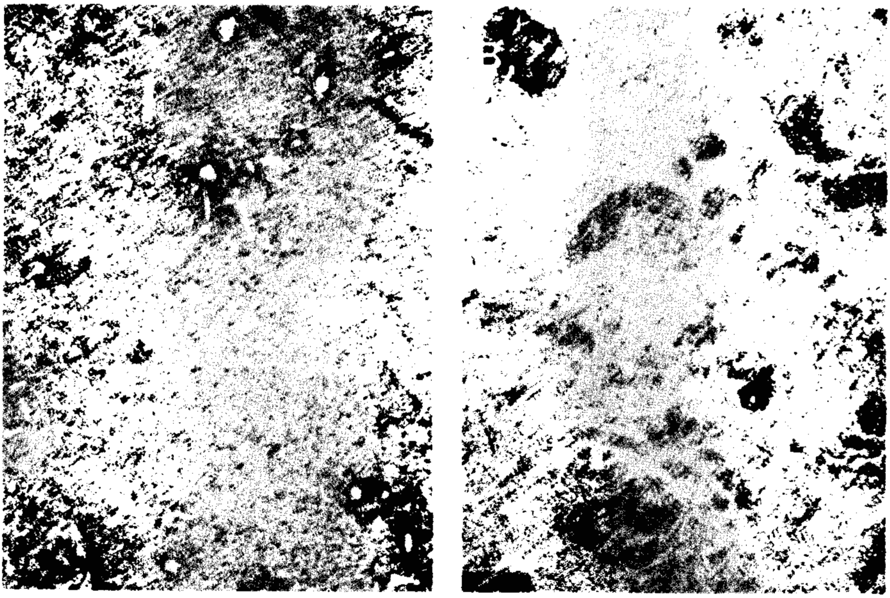
5. Method for measuring the area of air-filled horizontal cracks as a function of hydraulic pressure.

Large-pore continuity in disturbed and undisturbed plowpans in sandy loam soils. Plowpans in a sandy loam soil were disturbed by deep rototilling (23). After 2 yr the disturbed plowpan had lower hydraulic conductivity, higher pore volume, and lower bulk density than the remaining plowpan. The difference in hydraulic conductivity was explained by observing large-porecontinuity, made visible by stained channels, in thin sections of a compact groundmass (Fig. 6A). The disturbed plowpan had discontinuous, (unstained) compound packing voids between aggregates (Fig. 6B).

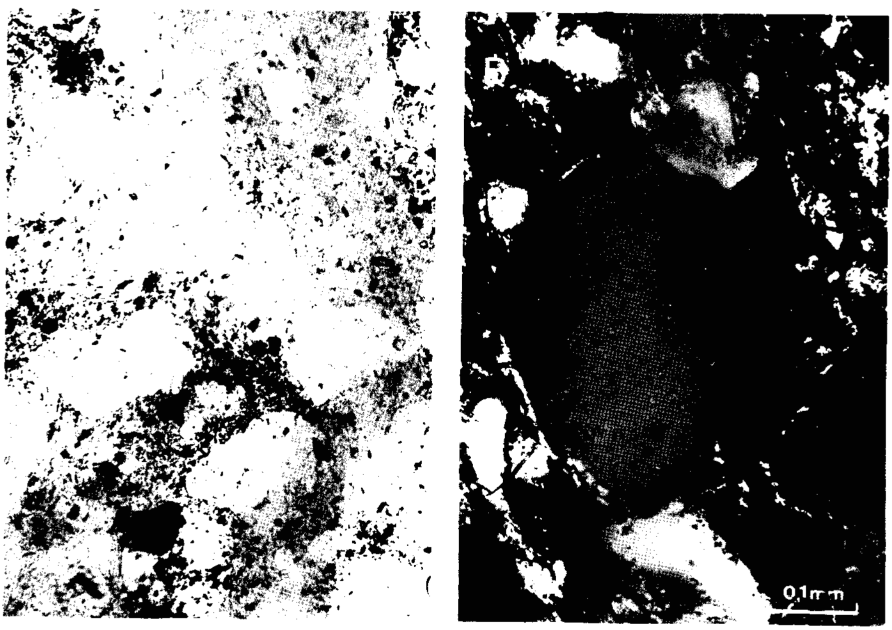
The study showed that large aggregates, made by deep tillage of this sandy loam soil, were unstable. They collapsed and closed the compound packing voids between the aggregates. Aggregate instability was a consequence of the soil microstructure composed of elementary sand, silt, and clay particles.

Tillage under wet conditions may puddle the soil, causing the clay particles to swell (3) and fill the pore space between the sand grains (Fig. 7A). The result is a soft, plastic soil with relatively high porosity that consists only of fine pores. Its hydraulic conductivity is relatively low.

Upon drying, the fine soil particles concentrate along the sand grains to form bridges (Fig. 7B). When rewetted, the bridges do not disappear, and the soil is slightly hard



6. Horizontal thin-section images of stained samples of a plowpan in a sandy loam soil (A) and of a disturbed plowpan (B). Lack of continuous macropores in B is indicated by the absence of stained pores (23).



7. Thin-section images of samples of a puddled sandy loam (A) and an air-dired sandy loam (B) on a gypsum plate show parallel orientation of clay paticles to sand grains. In the puddled soil, fine particles are dispersed between the sand grains. In the dried soil, they concentrate around the grains (voids are red) (3).

at that moisture content at which the puddled soil is soft and plastic,

Micromorphological data on microstructure, as shown here, help understand physical and mechanical soil processes and help formulate hypotheses.

USING MORPHOLOGY FOR SOIL PHYSICAL CHARACTERIZATION

Methodology

It is important to choose proper physical methods and applications when evaluating soil structure. It also is essential to describe soil structure before taking samples. At least 20 elementary units of soil structure should be represented in a good sample (7). The following are some examples of appropriate physical methods, applications, and sampling techniques(8).

Measuring hydraulic conductivity. Large soil samples are necessary for representative hydraulic conductivity measurements. Dyes can be used to determine local flow patterns in soils with natural peds, as in the previously described study. Column, cube, and crust methods require 15 to 20 litres of soil carved from the experimental plot. The block of soil must be encased in gypsum (4, 5, 10). Auger-hole sampling methods are unreliable because the wall of the hole puddles (16).

Measuring by pass flow. To measure bypass flow, undisturbed samples of surface soil are taken in plastic cylinders and sprinkle-irrigated. Bypass flow is measured directly in eight 6-litre samples. Although the samples are larger than normal, they often do not contain 20 peds. Correct cylinder placement in the soil is essential, and should be guided by structure descriptions made before sampling (13, 19).

Measuring water content and pressure. Variations in field moisture should be considered when measuring moisture content (as with a neutron moisture meter) or pressure (with a tensiometer). Soil structure should be studied before and after measurement devices are installed. Moisture distributions and preferential flow patterns also should be observed. Carefully recorded observations can explain some of the variability among replicate measurements.

For example, Bouma et al (9) reported different readings when using 8-cm and 5-mm tensiometer cups to determine infiltration patterns in a silt loam soil. Study of the soil structure showed that the large cups intercepted water–conducting macropores along which water entered the soil by bypass flow. They showed a brief period of saturation that was not shown by the small cups. The smaller cups only contacted the unsaturated soil matrix, which represented, in fact, the overall condition of the horizon.

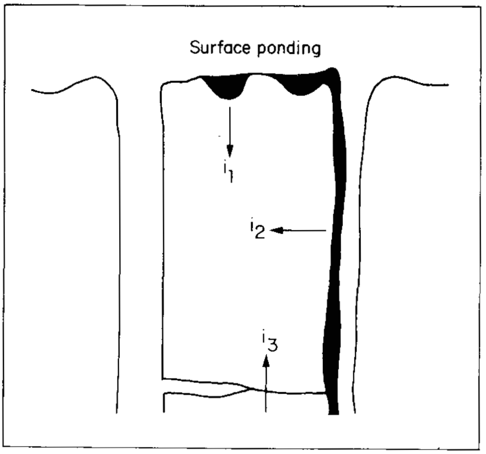
Simulation models

Complex flow processes in biporous soils with macropores can be simplified by submodels developed using soil morphological data. Three infiltration submodels are shown in Figure 8:

1. vertical infiltration between macropores at the soil surface (i_1);
2. water flow from the surface into the macropores after microdepressions on the soil surface are filled; and
3. partial or complete filling of the macropores and lateral infiltration into the unsaturated soil matrix (i_2).

A separate submodel for upward flow through unsaturated soil (i_3 in Fig. 8) is based on the dye method to show the effect of horizontal cracks.

Computer simulation, based on Darcy's Law and the continuity equation, and using CSMP or other user–friendly subroutines, facilitates infiltration submodeling, as shown in the following examples.



8. Schematic representation of water infiltration in a biporous soil, showing surface ponding, vertical infiltration (i_1), lateral infiltration along ped faces into peds (i_2), and upward flow (i_3).

Sprinkler-irrigating a clay soil. A model with three submodels was used to predict water infiltration during sprinkler-irrigation of a dry, cracked soil (21). Functions K-h, D-q, and h-q were measured, as was contact area S at two sprinkling intensities, and surface ponding. The observed high bypass flow (expressed as a percentage of sprinkling rate) was caused by low S values and relatively low surface ponding. Simulated conditions in which all vertical ped faces were available for lateral infiltration

(S = 20,000 cm^2) predicted no bypass flow because water was absorbed within 2 cm of the surface.

Flooding a dry, cracked clay soil. In the previous example, cracks were not filled with water, and water moved in narrow bands along the vertical walls of air-filled cracks. Flooding a dry soil causes water to pond and fill the cracks. The width, depth, and number of cracks per unit surface area determine available volume for storage. Infiltration occurs in the upper soil surface, and laterally from filled cracks.

A field study (17) showed that the volume of air-filled cracks available for water storage could be estimated by counting gypsum-filled cracks. In a simulation, lateral infiltration into the peds was calculated using a measured D-q function and the total length of cracks within a given horizontal cross-sectional area.

Flooding of soils with worm channels. When soils with worm channels are flooded, water penetrates rapidly to depth. A field and simulation study was made of vertical infiltration at the soil surface, worm-channel filling, and lateral infiltration into the soil matrix from the filled channels (9). Because worm channels have irregular morphology, measured rather than calculated infiltration rates were used because the latter assume channels to be perfectly cylindrical(20).

Upward, unsaturated flow in a cracked clay soil. Using the dye method, a K_{macro} curve (Fig. 2) was used to calculate water-table-to-root-zone fluxes in a heavy clay soil in the growing season. Simulated data and field measurements agreed well (14), but predictions were unrealistic when a K-curve for the peds was used to calculate upward fluxes.

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EFFECTS OF PUDDLING ON SOIL PHYSICAL PROPERTIES AND PROCESSES

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Abstract

Puddling processes and their effects on soil physical environment, rice production, and succeeding upland crops are reviewed. Soil aggregation, bulk density, soil strength, pore-size distributions, gas exchange, water retention and transmission, soil thermal regimes and formation of subsurface hardpans are discussed.

Puddling destroys soil aggregates, and thus changes other soil physical properties. Bulk density may increase or decrease depending on soil structural status before puddling. Soil strength decreases with puddling and water transmission pores are eliminated. Storage pores are less affected but residual pores are markedly increased. Puddling decreases gas exchange, hydraulic conductivity, and percolation losses and soil drying. Water retention at suctions higher than 10 kPa increases and soil temperature in the root zone declines. The influences of these changes on rice production are discussed.

Also described are the formation and effects of hardpans in lowland rice soils. The necessity of developing indices for evaluating puddled soils is stressed and attention is directed to unresolved questions concerning physical aspects of rice-based cropping systems.

PUDDLING

In most Asian countries, puddling is almost synonymous with rice culture, although in other parts of the world -- the United States, Australia, and parts of Europe and even in some Asian countries -- riceland is cultivated dry and then flooded.

Puddling generally refers to breaking down soil aggregates at near saturation into ultimate soil particles. Bodman and Rubin (3) defined puddling as the mechanical reduction of the apparent specific volume of soil. For a farmer, puddling is mixing soil with water to make it soft for transplanting and impervious to water (8). It controls weeds and reduces percolation losses of nutrients. The advantages and disadvantages of puddling in rice-based cropping systems were well documented by De Datta (8).

During puddling, soils undergo two deforming stresses: normal (load) stress, associated with compression, and tangential stress causing shear. Compression is most effective below, and shearing effects dominate above the upper plastic limit. The work done during puddling can be expressed by (3):

Total work in puddling	=	work done by normal stress before shear	-	work done by normal stress during shear	+	work done by tangential stress during shear

The ease and degree of puddling depend on soil type, moisture content, tillage implement, and cultural practices.

Maximum puddling occurs at moisture contents between field capacity and saturation (3, 21). At such moisture contents, the cohesion <u>within</u> soil aggregates is minimum, so shear planes may easily form. Moreover, when aggregates of dry soil are wetted, uneven swelling and explosion of trapped air also helps form shear planes. At moisture content below saturation, cohesion <u>between</u> the aggregates and clods is maximum, and movement of aggregates along each other and along the implement is therefore restricted. Consequently, the energy of the puddling implement is effectively transferred to shear and destroy the aggregates.

Soils with high cohesion <u>within</u> aggregates, caused by stabilizing agents sucn as Fe and A1 hydrous oxides, calcium carbonates, and organic matter, need a larger energy input for puddling. High clay content favors puddling, but kaolinitic clays are more difficult to puddle than montmorillonite clays. Similarly, Na-saturated clays puddle more easily than Ca-saturated clays.

Degree of puddling also depends on tillage implement and on intensity of puddling. Rotary implements generally are better for puddling than plows because their rotary motion continually changes the direction of the shear stress and hence matches the weakest fracture plane within a clod. Nevertheless, country plows, moldboard plows, disk harrows, angular puddlers, and rototillers also are effective. In quantitative studies of puddling, results often are variable because of influences of soil type and of the particular choice of puddling index.

EVALUATING THE SOIL PUDDLE

Bodman and Rubin (3) measured the degree of puddling as the decrease in apparent specific volume of soil after puddling. Taneja and Patnaik (32) used the fractional volume shrinkage of puddled soil, centrifuged at 2000 rpm, to characterize degree of puddling. Bhole (2) used viscosity of puddled soil as an index. Sinha (31) developed an index of puddling based on soil particle dispersion, calculated as the ratio of the volume of (puddled) soil after and before settling for about 48 h. A higher value indicates a greater degree of puddling. Aggregate size distribution and decrease in saturated hydraulic conductivity and percolation rate also have been used as indices.

However, no single index can satisfactorily describe a puddled soil. For example, puddling does not always decrease apparent specific volume. It may cause a decrease or an increase, depending on soil aggregation status, the nature of colloids and ionic concentrations in the soil solution (14). For soil dispersion, there are strong influences of electrolyte concentration. Moreover, if soil dispersion on puddling is low, loss of volume during settling also will be low, falsely indicating a high degree of puddling. Furthermore, percolation rate for this soil may remain high.

Decline in hydraulic conductivity or percolation rate may not be an unambiguous index of puddling, because soil compaction (without pulverization) also can decrease percolation (11). It may therefore be that for applications in rice research one should use a combination of indices that characterize both softness (for ease of transplanting) and permeability to water (for economy of water and nutrients). A joint index of bulk density and percolation rates may be effective. For routine work, the ratio of water-dispersible silt plus clay in puddled soil to the actual silt plus clay may be useful to determine the degree of puddling.

EFFECTS OF PUDDLING

Puddling influences physical, chemical, and microbiological soil properties, which in turn influence rice growth. Puddling has both short– and long–term effects on soil and on rice growth. This paper reviews only the physical effects of puddling in relation to rice growth and yield.

Short–term effects of puddling

Soil structure. Puddling destroys aggregates and peds. Wetting dry soil causes uneven swelling in aggregates and explosion of trapped air. The aggregates are slaked. Aggregates, depending on their stability, will be partially or completely destroyed if they are, submerged and subjected to repeated plowing, harrowing, or other puddling. A well–aggregated, porous soil is converted into a massive, plastic mud.

The puddled layer is neither structurally nor chemically uniform, but there is little information on stratification within puddled soil. A Japanese study showed that the upper 0-15 mm of the puddled layer is composed of fine particles, the middle layer is thin and porous with sandy shingles, and the lowest layer is massive without particle differentiation(26).

Chaudhary and Ghildyal (5) reported that puddling reduced mean weight diameter of aggregates from 1.70 to 0.36 mm. In a laboratory study (11) using aggregates smaller than coarse sand, puddling broke about 40% of the aggregates into fractions less than 0.05 mm. In an experiment in China (35), a change from double–cropped rice–wheat to triple–cropped rice–rice–wheat reduced microaggregate content by 50% between 1965 and 1976 (35).

Bulk density and soil strength. The effect of puddling on bulk density depends on soil aggregation before puddling. If puddling produces a parallel, closely packed structure from a well–aggregated open structure, bulk density increases. But puddling can also produce a more open structure, and hence decrease bulk density. Strong interparticle forces generally favor well–oriented structure, and weak interparticle forces favor open gel structure (14).

Puddling a well–aggregated, porous soil creates a massive structure with high bulk density (3, 11) that increases with drying because of soil shrinkage. A dried, puddled soil is compact and hard, and develops broad, deep cracks, de–

pending on clay nature and content. Puddling such a soil disperses particles and lowers bulk density.

Table 1 shows that as a result of puddling, surface-layer bulk density of a lowland clay declined from 0.83 to 0.53 t/m^3, and of a clay loam from 1.16 to 0.81 t/m^3, But as particles settle, bulk density of a submerged soil increases with time. Settling and consolidation may be due to reflocculation of .dispersed clay, and would depend on clay composition and on ionic concentrations of the soil solution. Sandy or kaolinitic soils settle faster than others. A report from Surinam (24) suggests that bulk density of a puddled soil under continuous submergence declines over time, with a consequent decrease in soil-watercontent at saturation from over 90% to as low as 20%.

Puddling decreases the shear strength of the surface layers. In general, shear strength decreases with moisture content and increases with bulk density (22).

Bulk density and shear strength are negatively correlated with growth and grain yield of transplanted rice (15, 17). In a field experiment, decrease of bulk density of a clay loam from 1.16 to 0.81 t/m^3 and decrease in cone penetrometer strength in the 0-10cm layer from 1.1 MPa to zero increased rice grain yield from 3.6 to 5.5 t/ha. Rice yields in dense soils probably are low because seedling roots are injured at transplanting and because the strong soil impedes rootgrowth.

Soil porosity. In a puddled soil, individual clay particles or particle clusters are in parallel rows within water-saturatedcapillary pores. Gas either is nonexistent or trapped in storage and residual pores. Aomine and Shiga (1) studied the structure of several Japanese rice soils after harvest. They identified a massive layer Ap 1 with

Table 1. Effect of puddling on bulk density of two soils (29).

Depth (cm)	Bulk density[a] ($t\ m^{-3}$)			
	Clay		Clay loam	
	NP	P	NP	P
0-10	0.83	0.53	1.16	0.81
10-20	0.91	0.68	1.23	1.09
20-30	1.00	1.02	1.29	1.27

[a] NP = nonpuddled, P = puddled.

very few pores in the top 1–2cm, followed by a relatively more porous layer Ap 2 to about 10 cm, underlain by a massive layer Ap 3.

The effect of puddling on porosity depends on the soil particle orientation in the puddled layer. If a parallel structure develops from an open gel structure after puddling, total porosity decreases. If a more open structure results from puddling, total porosity will have increased. Bodman and Rubin (3) reported 90-100% reduction in the noncapillary porosity in a silty clay loam. Jamison (18) observed about 80% reduction in pores >10 μm in a clay soil, with a corresponding increase in water-filled pores. However in our study, puddling a dry, lowland clay increased total porosity from 69 to 80%, and in a clay loam soil from 56 to 69%.

There are few studies on pore-size distribution in puddled soils because accurate measurements are difficult. The capillary rise equation, normally used in rigid, porous systems, is difficult to apply in a nonrigid, swelling system where structure changes as soil dries and shrinks. Other methods of measuring pore-size distribution also have weaknesses (14).

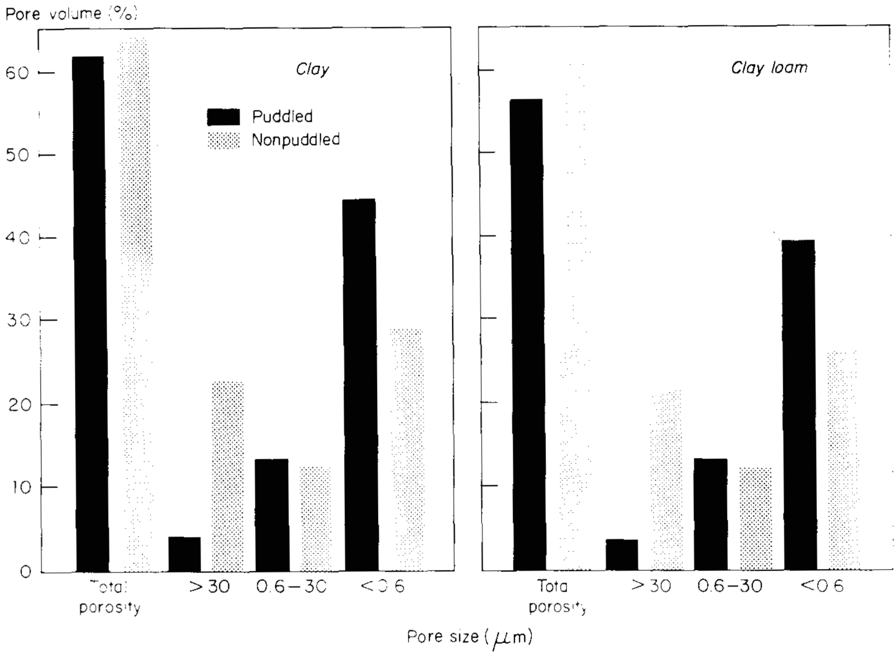
Figure 1 shows a comparison of pore-size distribution in puddled and nonpuddled clay and clay loam soils at IRRI. In each soil, puddling decreased pores >30 μm (transmission pores) by about 83% and increased pores of 0.6-30 μm (storage pores) and (0.6 μm (residual pores) by 7% and 52%. Changes in pore-size distributions strongly influence gas exchange, water retention and transmission, and soil evaporation.

Gas exchange. Diffusion coefficients of gases in water are about 10^{-4} of those in air. In soil water, the diffusion coefficient is further reduced by the solid matrix and by tortuosity. The effective diffusion coefficient in soil water (D_{sw}) relates to the diffusion coefficient in pure water (D_w) as:

$$D_{sw} = D_w \tau \phi V_w$$

where τ is the tortuosity factor, ϕ a factor accounting for interaction between gas and soil (usually = 1), and V_w the volumetric moisture content.

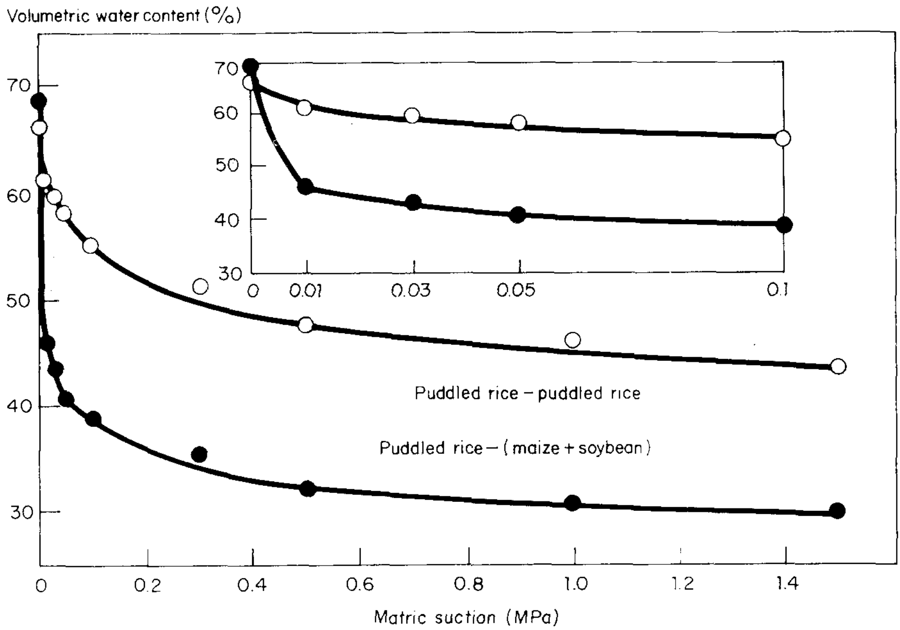
In a submerged, puddled soil, gas exchange, especially of oxygen, between soil and atmosphere is severely restricted. Oxygen concentration declines and carbon dioxide concen-



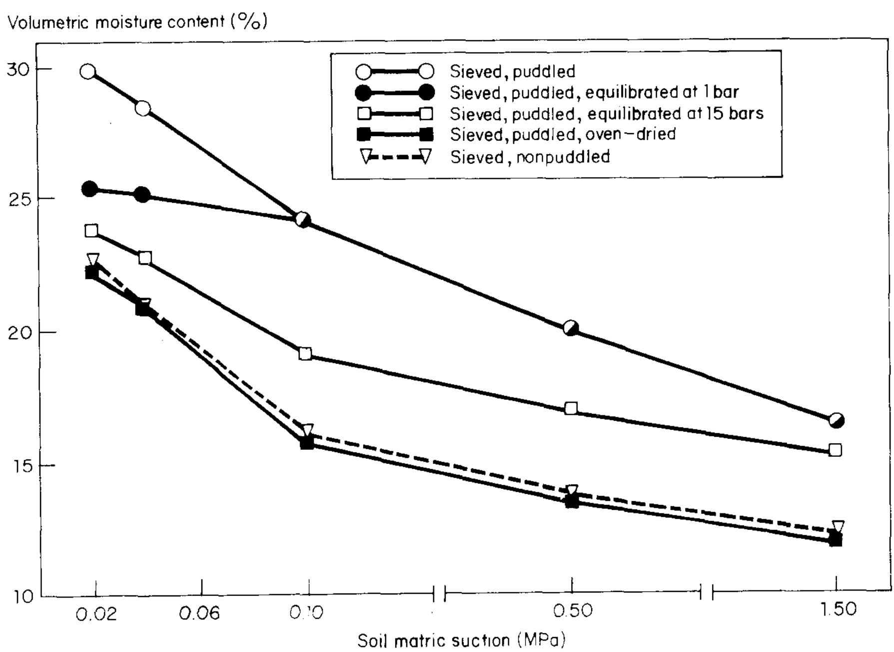
1. Effect of puddling on pore-size distribution of 2 soils (P. K. Sharma and S. K. De Datta, unpubl.).

tration increases. Some soils may generate 2.5 t carbon dioxide/ha in 3 wk of submergence (12). In puddled soils, carbon dioxide concentrations usually are not toxic to rice because the required oxygen is transported in the roots by intercellular gas spaces. For most upland crops, critical oxygen diffusion rate (ODR) is 18×10^{-5} kg $m^{-2}h^{-1}$, and for rice (22) is 2.4×10^{-5} kg $m^{-2}h^{-1}$. But in soils receiving high amounts of easily decomposable organic matter, carbon dioxide levels might become toxic.

Water retention and transmission. Eliminating noncapillary pores in puddled soils usually lowers water retention for potentials above –0.01 Mpa. At lower (more negative) potentials, and hence over the range –0.01 to –1.5 MPa, water retention in puddled soils always exceeds that in nonpuddled soils (33, 35). Figure 2 shows moisture desorption curves for a clay soil under two crop rotations: puddled rice – puddled rice, and puddled rice – (maize + soybean). Drying brings soil moisture characteristics of puddled soils closer to those of nonpuddled ones (Fig. 3); moreover, resaturation does not restore to a dried puddled soil its original high water retention capacity (33).



2. Effect of puddling on water retention in a clay soil at different matric potentials (P. K. Sharma and S. K. De Datta, unpubl.).



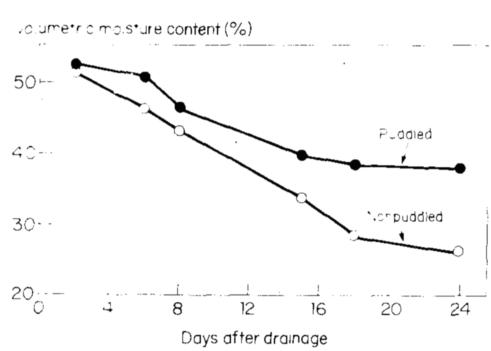
3. Effect of different predrying treatments on water characteristic curves of a silty clay loam soil (33).

Puddled soils dry more slowly than unpuddled soils (15, 16), probably because the higher unsaturated hydraulic conductivity of puddled soils can keep surface soil wet during evaporation by supplying water from lower layers. Also, because of increased water retention at a given suction, more energy is needed to evaporate the same amount of water from a puddled than from an unpuddled soil. Thus a puddled soil may take several weeks or months to dry and to reach a workable moisture content (Fig. 4). Rice grown on a puddled soil may be less affected by drought than rice grown on a granulated soil (10). Under severe drought, however, when soil begins to shrink and crack, restricted root development makes rice perform worse in puddled than in well–aggregated soil under the same evaporative demand (27).

Closely packed parallel particles in puddled soils reduce saturated hydraulic conductivity and percolation (8, 15, 34). Subsurface hardpans (13) or a constant shallow water table further limit percolation (34). Cheng (35) found that percolation rate declined from 9-15 mm to 2–10 mm/d when a cropping system changed from rice–wheat to rice–rice–wheat

Reducing percolation improves water and nutrient efficiency in rice fields. In puddled soils, increased solubility (25) and decreased leaching (10, 28) maximize nutrient efficiency. Increasing percolation adversely affects water and nutrient economy and grain yield ([Table 2] 10, 12, 20, 30). However, some percolation may be essential for higher grain yields in soils that regularly receive high amounts of easily decomposable organic matter.

Thermal properties. Puddling affects thermal properties of soil by changing bulk density, moisture content, and percolation rate. Thermal conductivity (l) and volumetric heat capacity (C) increase with bulk density and soil–



4. Time drying curve of the top 5 cm of puddled and nonpuddled soil at rice harvest (15).

Table 2. Effect of puddling on leaching losses of nutrients (29).

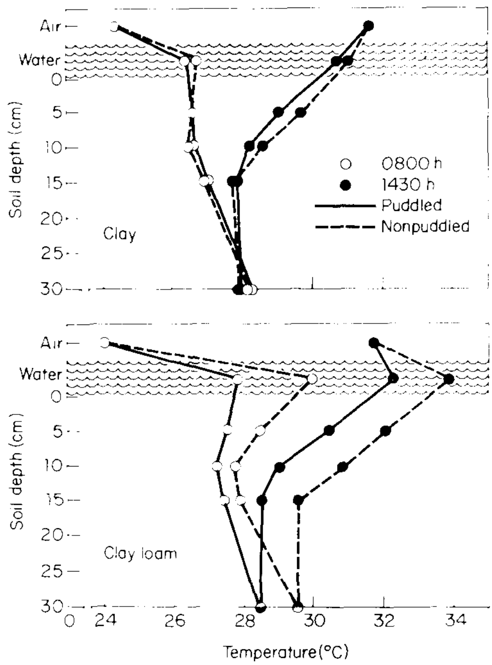
Treatment	Percolation rate (mm d^{-1})	Leaching losses (kg ha^{-1})						
		NO_3^-	NH_4^+	P	K	Fe	Mn	Zn
					Clay soil			
Puddled	1.8	1.1	0.43	0.27	23	0.85	1.86	0.18
Nonpuddled	2.2	1.5	0.37	0.29	25	0.60	1.02	0.13
LSD	-	0.3*	ns	ns	ns	ns	ns	ns
					Clay loam soil			
Puddled	2.2	1.6	0.33	0.21	14	1.07	1.84	0.12
Nonpuddled	8.5	8.7	1.62	0.86	71	1.28	1.13	0.40
LSD	-	2.6**	0.34**	0.19**	30**	ns	ns	0.07**

moisture content. Thermal diffusivity (l/C), which determines the rate of change of soil temperature, also increases with increasing moisture content, reaching a maximum at moisture contents corresponding to about –0.1MPa and thereafter declining, High percolation rates may increase or decrease root zone temperature depending on irrigation water temperature.

We studied temperature profiles (Fig. 5) in submerged puddled and in submerged nonpuddled clay and clay loam soils. (We could find no published information on such profiles.) For the clay loam, temperature was higher for nonpuddled than for puddled soil, but for the clay soil temperature was unaffected by puddling -- although bulk density, about 30% higher in nonpuddled soils, differed similarly for both soils. Indeed, soil temperature appeared to be influenced more by percolation rate of the hot irrigation water than by bulk density. Thus in the clay loam, percolation rate in the nonpuddled soil (8.5 mm/d) was significantly higher than in puddled soil (2.2 mm/d). For the clay, percolation rates (1.8 and 2.2 mm/d) were the same in puddled and nonpuddled soil. Additionally, irrigation water was 2–3 K cooler in the clay than in the clay loam. Influence of percolation rate on the temperature profile in a puddled soil is shown also in data from a greenhouse experiment (Fig. 6). Because soil temperature affects rice throughout the growth cycle (6), more research is needed into the thermal properties of puddled soils.

Long-term effects of puddling

Long-term puddling forms a hardpan in the subsoil below the puddled layer. It may take 3 to 200 yr for a hardpan to

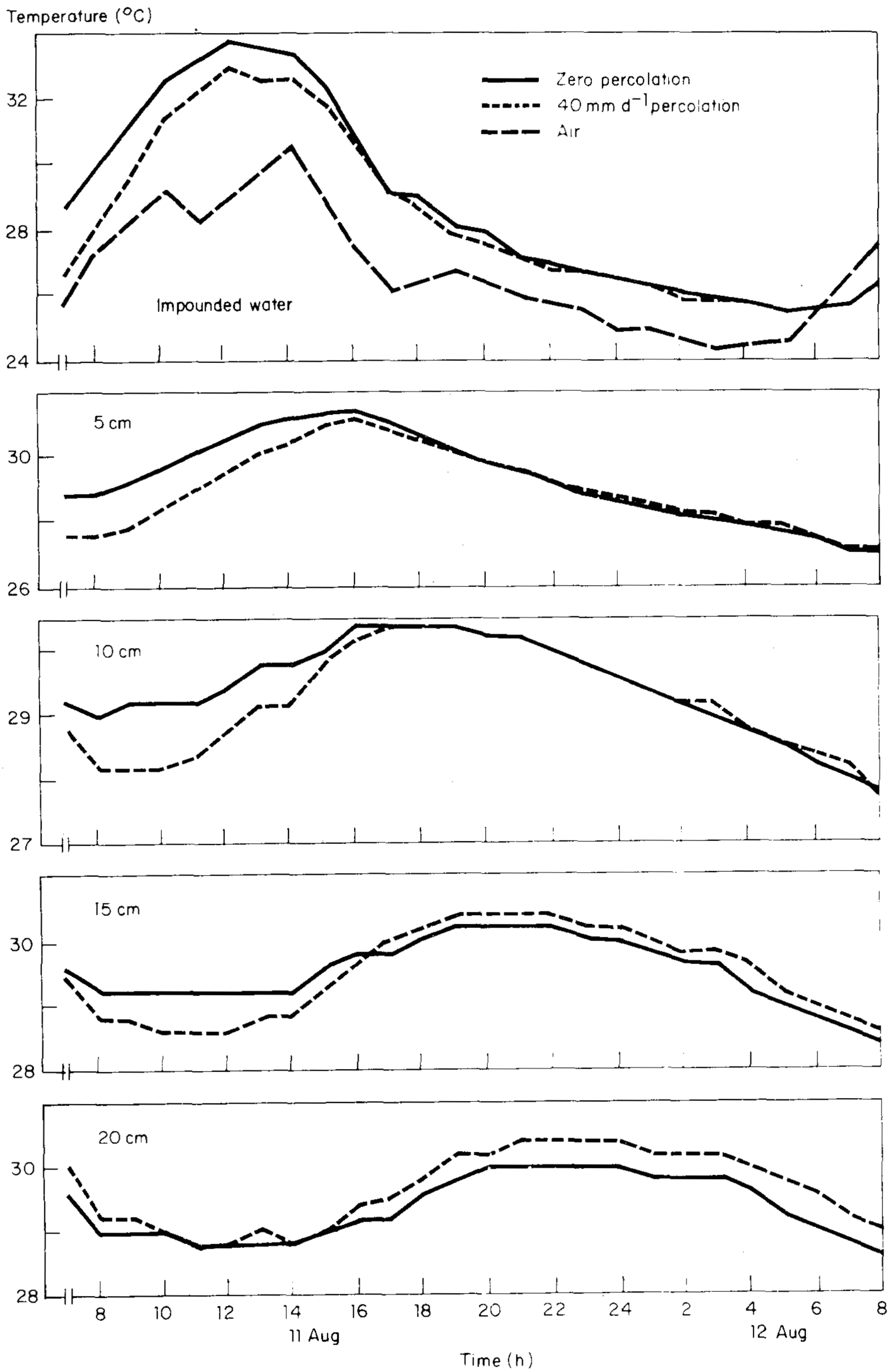


5. Temperature profiles in puddled and nonpuddled clay and clay loam soils (29).

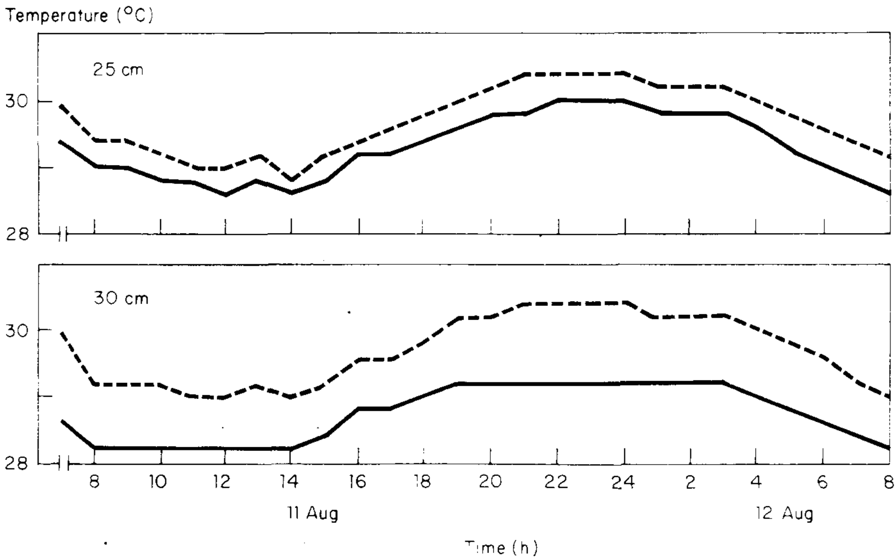
form, depending on soil type, climate, hydrology, and puddling frequency (24). Subsurface hardpans develop from physical compaction and precipitation of Fe, Mn, and Si.

Compact, 5- to 10-cm thick layers which occur in lowland rice soils between 10 and 40 cm depth and that have higher (dry) bulk density and lower total porosity and water permeability than the over- and underlying soil horizons were called plowpans by Koenigs (in 24) and traffic pans by Moormann and van Breemen (24). Tables 3 and 4 show some physical properties of a hardpan in a lowland clay loam (35). Hardpans are associated with the use of machinery and with compaction caused by farmers and animals during tillage, transplanting, and weeding (13).

Chemically cemented pans are formed in the oxidized subsoil, usually 15- to 20-cm deep, by precipitation of Fe, Mn, and Si from upper, reduced soil layers. Soils with slowly permeable subsurface horizons, oxidized subsoils, low pH, high concentrations of easily reducible Fe and Mn, and easily decomposable organic matter favor chemical precipitation. Because continuously submerged soils have excessively reduced conditions, Fe- and Mn-pans form very slowly. Under favorable conditions, Mn- and Fe-pans may develop in 8-40 yr (24). Ferrolysis (4) is another long-term effect of puddling that may lower soil productivity.



Temperature (°C)
Zero percolation
40 mm d⁻¹ percolation
Air
Impounded water
5 cm
10 cm
15 cm
20 cm
32
28
24
30
26
29
27
30
28
30
28
8
10
12
14
16
18
20
22
24
2
4
6
8
11 Aug
12 Aug
Time (h)



6. Effect of percolation rate on the temperature profile in a submerged silty clay soil (P. K. Sharma and S. K. De Datta, unpubl.).

Table 3. Bulk density, total porosity, aeration porosity at field capacity, and saturated hydraulic conductivity of a typical lowland soil (35).

Soil property	Plow layer	Plowpan	Below plowpan	Substratum
Bulk density ($t m^{-3}$)	1.2	1.4	-	1.6
Total porosity (%)	53	44	-	42
Aeration porosity (%)	15	2	4	Negligible
Saturated hydraulic conductivity ($cm\ d^{-1}$)	1038	1.7	3.1	1.0

Table 4. Pore-size distribution in a typical lowland soil (35).

Pore diameter (mm)	Plow layer (29 samples)		Plowpan (28 samples)	
	%	% of total	%	% of total
>0.2	11.5 ± 3.1	22	5.5 ± 2.3	11
0.2 - 0.1	0.9 ± 0.5	2	0.4 ± 0.1	1
0.1 - 0.05	1.1 ± 0.3	2	0.5 ± 0.1	1
0.05 - 0.01	2.6 ± 0.9	5	1.7 ± 0.7	3
0.01 - 0.005	1.6 ± 0.4	3	1.3 ± 0.5	3
<0.005	34.5 ± 3.1	66	40.9 ± 3.2	81

A compact subsoil layer should benefit lowland rice because it limits percolation of water and leaching of nutrients. Mallick et a1 (23) wrote that a layer of 1.65 t/m^3 bulk density at 20 cm depth reduced the water requirement of a rice crop by 20 to 40%. There are other similar findings (16). However, we can find no data on the effect of hardpans on the growth and yield of puddled rainfed rice, either for conditions of water sufficiency or water shortage.

Such effects may vary with soil texture as well as bulk density. Pore-size distribution, which is influenced by texture, has more effect on root growth and distribution than total porosity (19).

Subsurface compact layers have many names -- plowpan, traffic pan, hard layer, compacted layer, restricting layer, impermeable layer -- that sometimes indicate cause and sometimes effect. They should be characterized by location, shear strength, and porosity. Suitable terminology should be established.

IS PUDDLING ESSENTIAL?

Because puddling is labor- and capital-intensive, and because it creates soil physical conditions detrimental to upland crops in rice-basedcropping systems, it is logical to ask whether puddling is essential for rice culture and, if yes, under what conditions.

Zero and minimum tillage have produced grain yields of transplanted rice similar to those from puddling (7, 9). Sanchez (28) concluded that puddling reduced percolation losses of water and nutrients, but found no evidence that puddling improved nutrient uptake by rice. Our field data gave similar results. These findings imply that the only relevant benefits of puddling are the creation of soft tilth, reduction of water and nutrient losses, and weed control. Therefore, other tillage operations that can create those conditions should produce similar rice yields,

In submerged, nonpuddled soils, seedling roots are damaged at transplanting, and strong soil limits root growth. Seedling growth is slower and crop stand poorer than in puddled soil. Direct seeding may be a substitute for transplanting in such soils.

Crop establishment and weed control problems encountered under zero tillage are lessened if minimum tillage is undertaken, and the field then submerged (9). Hence, in soils that disperse easily on wetting or that have an imper-

Table 5. Grain yield of transplanted lowland rice in zero-tillage, minimum-tillage, and conventionally puddled plots (P. K. Sharma and S. K. De Datta, unpubl.).

Treatment[a]	Grain yield ($t\ ha^{-1}$)
Zero tillage	4.3
Minimum tillage	5.5
Conventional puddling	5.5
LSD (5%)	0.5

[a] Minimum tillage = 1 dry rototilling + submergence, conventional puddling = 2 wet plowings (carabao) + 3 harrowings.

meable subsoil that limits water permeability or that experience a constant shallow water table, minimum tillage may be substituted for puddling (Table 5). Minimum tillage followed by submergence may not only save money and energy but may reduce turnaround time for the subsequent upland crop. More research is needed to test this hypothesis.

In highly permeable soils, however, such as those with sandy to medium textures, or well-aggregated Oxisols and Andepts, puddling is essential for lowland rice production. Soil compaction may be a useful alternative (11).

RESEARCH GAPS

Although some information is available on the effects of puddling on rice growth and yield and its consequences in rice-based cropping systems, research on the following topics is much needed:

- identification of soils and cropping systems that do not require puddling for rice production;
- development of suitable indices to characterize puddled soils;
- thermal regimes of puddled soils in relation to rice production;
- effect on rainfed lowland rice of subsurface layers of various pore-size distributions and shear strength;
- long-term comparison of minimum tillage and puddling in terms of modifications in soil physical environment and production of lowland rice and succeeding rainfed upland crops; and

- alternative tillage techniques for upland crops following lowland rice with the objective of reducing turnaround time.

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AGGREGATE CLASSIFICATION AND SOIL PHYSICAL PROPERTIES FOR RICE-BASED CROPPING SYSTEMS

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ABSTRACT

Simple tests are described for dividing soil aggregates into seven classes. Possible treatments for reducing the hydraulic conductivity of a soil layer to a satisfactory level for rice production are discussed in terms of these aggregate classes. Recommendations are based on experience in reducing seepage through subsoils for dams. The ease of creating tilth for a subsequent dryland crop is also related to the class of aggregates and the tillage used for rice.

Attention is drawn to some possible beneficial effects on soil structure of organic compounds released during rice farming as shown by ultrastructural examination.

AGGREGATE CLASSIFICATION AND SOIL PHYSICAL PROPERTIES FOR RICE–BASED CROPPING SYSTEMS

For efficient rice production on flooded soils, saturated hydraulic conductivity should be small enough to prevent rapid loss of ponded water, yet large enough to allow any toxic substances to leach away. A seepage rate of 1 – 5mm/d is necessary, indicating an average soil hydraulic conductivity of 1-5x10^{-5} mm/s for unit hydraulic gradient.

Soil commonly is puddled for lowland rice. Puddling usually reduces hydraulic conductivity by destroying surface aggregates and compacting the underlying soil. Further compaction occurs during planting and weeding. However, if a surface soil is puddled and remains dispersed, dense clods or crusts form when it dries, making it difficult to prepare a seedbed for a subsequent dryland crop. Additionally, any subsoil compaction will impede root growth of the dryland crop and should be avoided.

On certain soils puddling may be unnecessary. Either no treatment is required or conductivity can be reduced sufficiently by compacting the soil at a water content that is less than the maximum water content that can be attained in the field without puddling, i.e. field capacity.

Changes in the hydraulic conductivity of a soil layer due to an applied stress depend on the magnitude of the stress, the strengths of the bonds between the clay particles, and the surface area of the clay. The ease with which the hydraulic conductivity of a soil layer can be changed is largely determined by the strengths of bonds between clay particles, the surface area of the clay, and the magnitude of applied stresses. The average strength of the bonds depends on factors such as pH, and organic matter content and composition.

Simple tests that integrate these properties have been developed by observing the coherence of aggregates in water. Based on the tests, soil aggregates have been divided into seven classes. A similar classification has helped diagnose structural problems in dryland agriculture (10).

This paper considers possible relations between the minimum treatment necessary to reduce the hydraulic conductivity of a soil to the required level and the class number of aggregates from the surface and immediate subsoil. The consequences of soil structural alteration for a subsequent dryland crop are discussed for each treatment and class number. The last section draws attention to the possible beneficial consequences of rice culture on bonding between clay particles by organic compounds released during crop growth, and on pore space developed by root activity.

AGGREGATE CLASS AND HYDRAULIC CONDUCTIVITY OF SOIL FOR RICE

The appendix describes an aggregate classification system and gives practical details for using it,

Suggestions for treating a subsoil to reduce hydraulic conductivity to the level required for rice are based mainly on laboratory experiments on the conductivity of compacted beds of subsoil aggregates typical of a given class. The results have helped predict the severity of seepage losses from darns (4, 5).

Excluding soils that disperse under an osmotic stress only (classes 1, 2), it is useful to define a water content for dispersion (q_D). It is the maximum water content at which a soil can be remolded and then a portion immediately immersed in water without the subsequent appearance of dispersed clay (5, 6). In the field, a soil must be stressed at a water content $>q_D$ if the clay present is to be disaggregated and so cause the conductivity to be severely reduced. Without puddling, the maximum water content at which a soil can be compacted is field capacity. The water uptake of unsheared soil at 10 kPa suction (q_{10}) is a useful approximation of this state. when a surface soil is puddled, the underlying soil will be compacted at a water content greater than q_{10}.

The ability of organic matter to act as a dispersant in wet-sheared soil must be considered for surface soils (3, 6). Bonding by organic matter may be sufficient to prevent aggregate slaking, yet complete dispersion nay occur in water after remolding the soil at its q_{10} value.

Table 1 lists suggested procedures for reducing the conductivity of soils to suit rice. Subsoil classes 1 and 2 include many soils used for rice-growing in Australia (for example, the soil used for Fig. 1, 2). The subsoil swells enough when the soil is flooded that seepage losses are usually small. Class 3 soils usually do not need to be puddled. It only is necessary to app1y a mechanical stress to the aggregates when the soil water content is greater than q_D. For example, pulling a ducksfoot cultivator through the subsoil when the soil is near field capacity should produce a low conductivity layer.

Table 1. Possible treatments to reduce the hydraulic conductivity of a subsoil to ~ 10^{-5} mm/s. Treatments are suggested according to the numerical (1-7) classification of aggregates. Consequent effect on the surface aggregates are listed in the final column.

Aggregate class		Mechanical treatment required on subsoil	Resultant condition of surface soil
Surface	Subsoil		
Any	1, 2	None	Unchanged
3	3	Shearing at $q > q_D$	Unchanged
4	4	Puddling at plastic limit	Flocculated paste
5	5	Puddling at $q >> \theta_{10}$	Part dispersed
6	6	None available	No change
-	7	None available	-

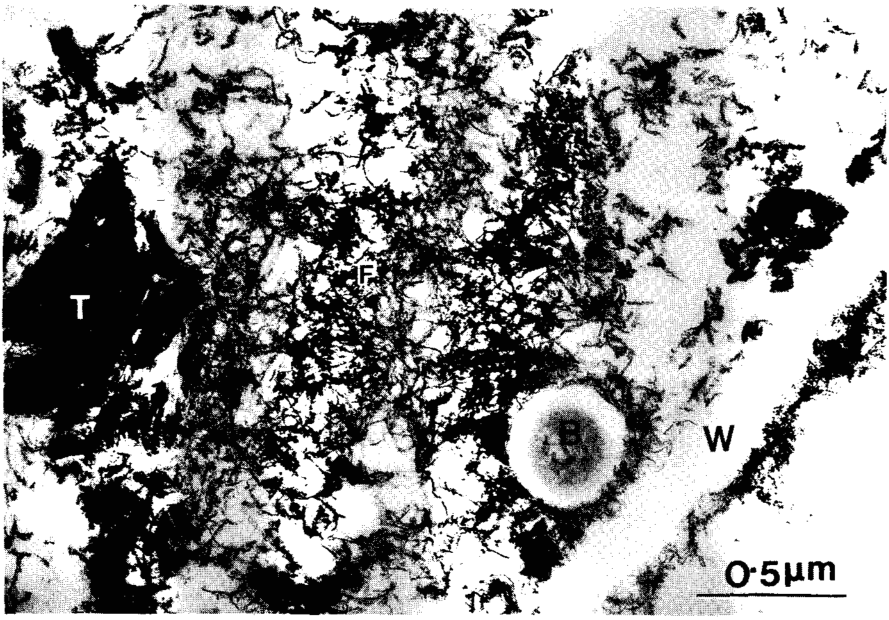
To compact class 4 soils, a water content greater than the plastic limit is required. For such soils, the plastic limit is greater than θ_{10}; therefore puddling is needed. After puddling, the surface soil will flocculate due to the divalent ions present, so that the reduction in conductivity is confined to the subsoil. For class 5 soils also, compaction at water contents greater than θ_{10} and the plastic limit is necessary to reduce conductivity. Puddling surface soil also will somewhat reduce conductivity, depending on the actual degree of dispersion. The conductivity of class 6 subsoils can be reduced to the required level by compaction, but the effect is temporary, and conductivity increases rapidly with time. Class 6 surface soils are not dispersed by puddling.

Layers of class 7 aggregates have the permeability of gravel. Such subplastic layers (13) occur in the subsoils of rice soils in the Riverina and cause excessive seepage losses (17).

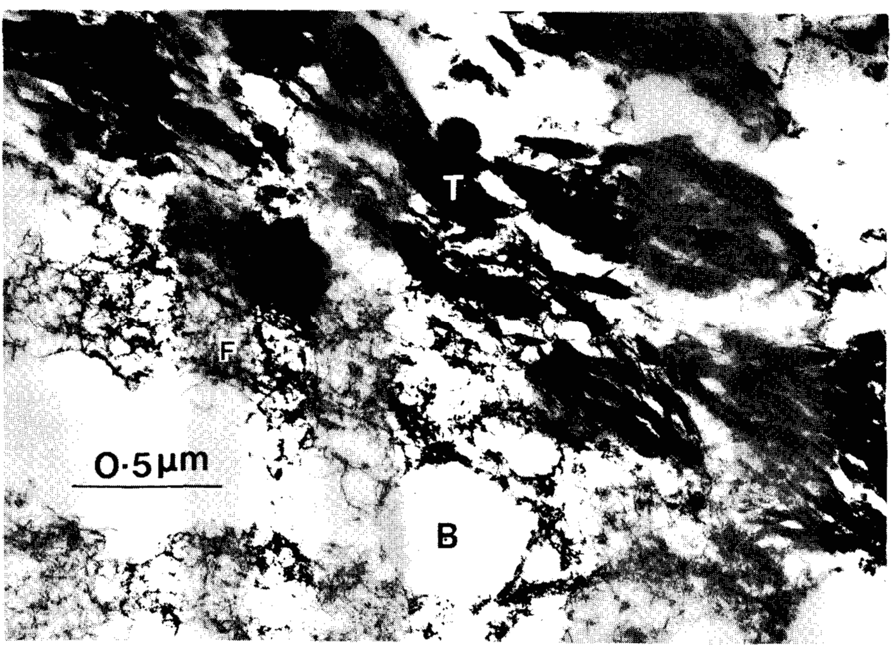
AGGREGATE CLASS AND SOIL STRUCTURE FOR SUBSEQUENT DRYLAND CROPS

The soils characterized in line 1 of Table 1 are ideal for rice but may present difficulties for a subsequent dryland crop because crusting reduces water entry. A small surface dressing of gypsum to last through the dryland crop could be useful (11).

If class 3 soils are puddled, the surface soil will be dispersed. On drying, dense clods or crusts form, depending on the degree of soil shrinkage. Even if the suggested manipulation of the subsoil reduces hydraulic conductivity



1. Ultra-thin section of the rhizosphere of a 4-wk-old rice plant. The root came from the saturated top 10 rnm of a Pellustert. The rice was seeded onto flooded, unpuddled soil. Note the outer wall of the root epidermis (W), the network of fibrils (F) surrounding the bacterium (B) and clay tactoid (T).



2. As for Figure 1, but illustrating the alignment of the tactoids.

sufficiently for rice, care must be taken to preserve the fragile structure of the surface soil. A small dressing of gypsum or carbonate would again help prevent structural deterioration (5).

Puddling may not be too harmful to the structure of class 4 soils. When they dry the surface soil should self-mulch and form a good seedbed. Because of a hysteresis effect, cracks that form when the compacted subsoil dries will not close when the soil is rewetted, and root penetration should be satisfactory. Irreversible cracking is a problem with dams constructed of class 4 soil because if the soil dries, puddling must be repeated to reduce hydraulic conductivity. Class 5 subsoils are similar. The status of class 5 surface soils after rice cannot be predicted because it depends on organic matter transformations that may take place during rice growth.

EFFECTS ON SOIL STRUCTURE OF ORGANIC COMPOUNDS PRODUCED UNDER RICE

Under the anaerobic conditions that prevail (except near live rice roots) in a rice soil, a variety of low molecular weight compounds develop from incorporated organic matter (16). If these compounds are adsorbed by the clay, the clay’s ease of dispersion increases, thus decreasing the class number or the aggregates and also the hydraulic conductivity.

On the other hand, Foster (8) demonstrated, through histochemical tests on ultra-thinsections of the rice rhizosphere, that polysaccharides are released both from the roots and associated bacteria. In sections cut from the same material, networks of fibrils about 20 nm in diameter are very evident (Fig. 1). They are much larger and more electron-densethan the usual fine granular staining due to polyuronides. The fibrils surround the clay tactoids (7) and bacteria (Fig. 2). Similar structures were found on a section of a rice root from IRRI (Foster, unpublished). The fibrils probably are carbohydrates impregnated mainly with Fe, because they disappear if the ultra-thin section is briefly treated with dithionite in a citrate buffer (14), but cavities do not form. The general alignnent of the tactoids in Figure 2 probably is caused by radial expansion of the root (9). If pores with stabilized clay cutans develop to the size of rice roots (400-1000 µm), every attempt should be made to preserve these pores for the succeeding crop.

CONCLUSIONS

In rice-based cropping systems, the low-permeability soil structure necessary for rice must be changed for the subsequent dryland crop to allow easy water entry and free drainage. The aggregate classification system outlined here is a simple way of indexing the ease with which the structure of a soil can be manipulated by mechanical and osmotic stresses.

The effectiveness of the treatments suggested for reducing hydraulic conductivity must be verified through field experiments, as must the predictions for the structural state of the surface soil after rice.

Little work has been done to determine the effect of organic compounds generated during rice growth on bonding between clay particles. A useful start would be to observe changes over time in the class number of the various soil layers, both near and away from roots.

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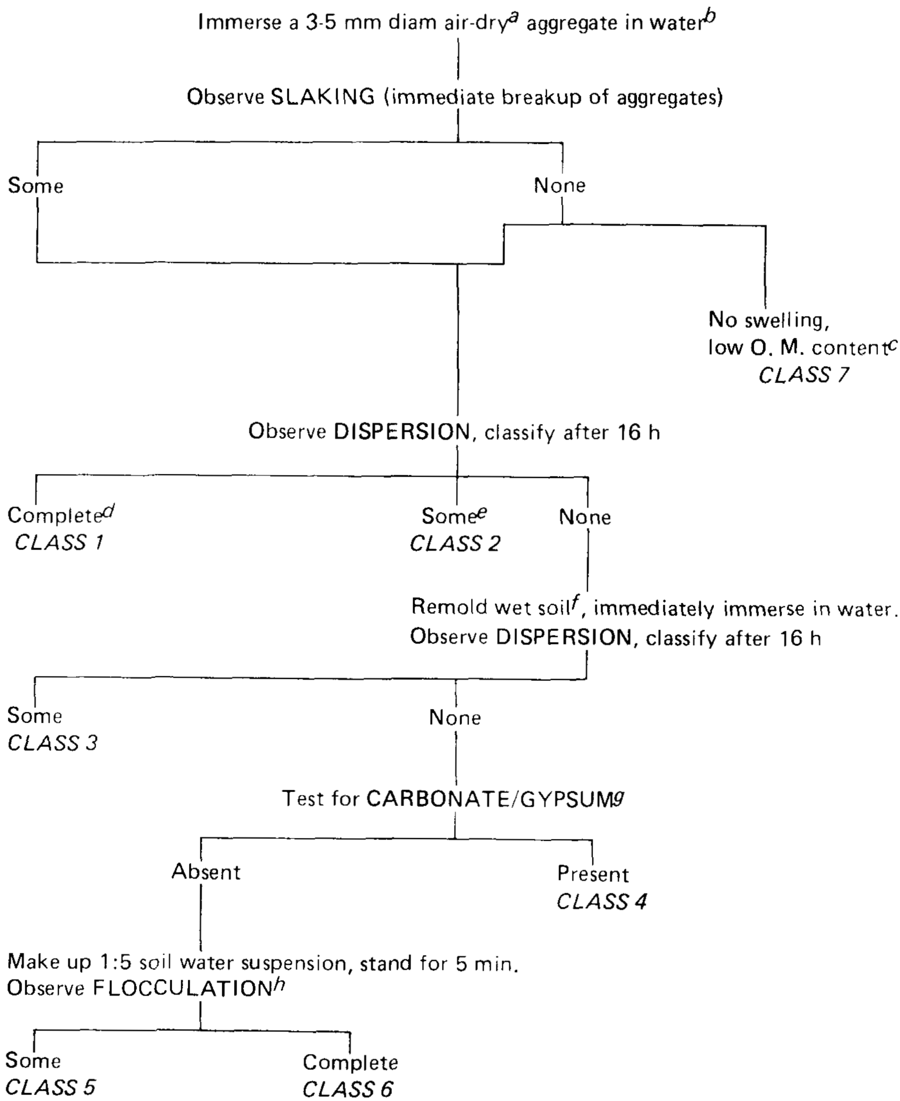
Appendix. Aggregate classification (after Emerson, 1967)



Explanatory Notes

a. Aggregates must be air-dried, not field moist or oven-dried.
b. Fifty ml of water in a squat 100-ml beaker. The beaker should be on a stable surface. The surface should be black to make observation easier. The beaker should be

covered with a watch glass to reduce evaporation and should not be disturbed. For initial testing, the water should be distilled or deionized, or rainwater. The tests can be repeated using irrigation water, where appropriate.

c. Aggregates are stabilized by inorganic cements.

d. With complete dispersion only sand grains remain and are surrounded by a cloud of clay.

e. The degree of dispersion of air-dry aggregates is frequently variable due to soil heterogeneity. Tests should be in triplicate (12).

f. Spread 5 g of <2 mm air-dry soil as a thin layer on a sintered glass funnel containing distilled water at 10 kPa suction. After 24 h, remove an aliquot, remold for 30 s using a spatula and quickly make two 3-mm-cube aggregates using a square section brass mold. Immerse one aggregate <u>immediately</u> in water as in (b) to avoid any thixotropic increase in strength; measure water content of the other. An alternative is to bring soil to its plastic limit and roll balls of about 3 mm diameter (1).

g. Check for carbonate/gypsum using HCl/acetone (15).

h. Place a 2 g air-dry soil sample in a test-tube and add 10 ml distilled water. Shake vigorously for 10 min. Stand for 5 min. and note whether suspension has flocculated completely, .i.e. some clear supernatant is visible.

STRUCTURE, STRUCTURAL STABILITY AND NATURAL RESTRUCTURING OF LOWLAND RICE SOILS

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ABSTRACT

Soils under rice cultivation have distinct physical and chemical properties and morphologies. The structure of plowed layers of artificial hydromorphic soils undergoes repeated dynamic changes with alternate flooding and draining. Soil aggregates are destroyed and soil flocculates when cementing agents become flocculating agents under reducing conditions.

Alternate flooding and draining reduce ped development in plowed layers, Typical peds are massive and blocky after drainage and massive under flooding. The aggregate content of these soils is thought to be an index of the strength of interparticle bonds. Rice cultivation restructures the subsoil and forms a distinct plowpan with illuviated Fe and Mn oxides and dense, blocky, or prismatic peds in horizons below the plowpan.

STRUCTURE, STRUCTURAL STABILITY, AND NATURAL RESTRUCTURING OF LOWLAND RICE SOILS

There are two groups of lowland rice soils, based on pedogenesis. Groundwater soils are naturally hydromorphic and poorly drained. Surface-irrigation soils are artificially hydromorphic and well-drained.

Artificial hydromorphism is caused by alternate flooding and draining in rice cultivation, and gives soils special physical and chemical properties. Artificial hydromorphism usually occurs in soils with low groundwater tables where irrigation water seeps through the soil profile. It does not occur when the groundwater table is high, as in gley soils, because rice cultivation does not then greatly change the water regime and soils retain their natural characteristics (16).

STRUCTURE OF PLOWED LAYERS

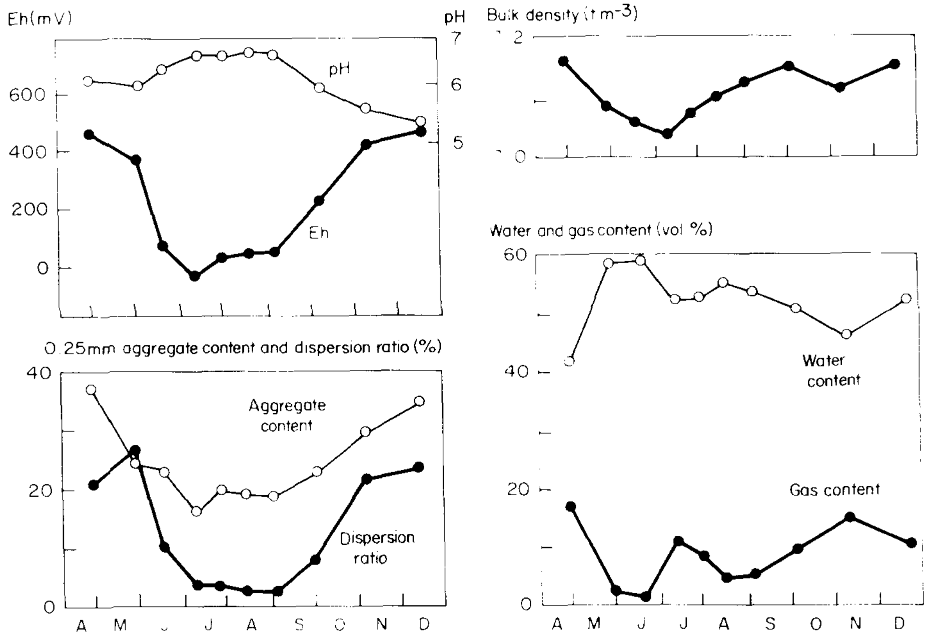
Seasonal changes

Seasonal flooding and draining cause repeated dynamic changes in the structure of plowed layers in well-drained lowland rice soils (4, 12, 13, 14, 21).

Saito and Kawaguchi (21) studied a clay loamy brown lowland rice soil. Moist 10- to 15-mm clods were taken from core samples and shaken with water for 15 min. Content of aggregates larger than 0.25 mm and the dispersion ratio of particles finer than 0.02 mm were measured in a 4% suspension using wet-sieving and pipette techniques.

Tillage, flooding, and puddling break up the aggregates and increase the dispersion ratio (Fig. 1). Interparticle bonding gradually weakens and reduction leads to destruction of aggregates. Reduced soils flocculate, with flocs of 0.04- to 0.05-mm equivalent spherical diameter, during measurement of the dispersion ratio. Aggregate content and dispersion ratio remain very low until the soil is drained.

Bulk density decreases with flooding and puddling, reaching a minimum in early July. At that time, gas content, which decreases greatly at puddling (Fig. 1), is highest. Flocculation, gas evolution, and swelling reduce bulk density. As gas escapes and solids settle, bulk density gradually increases. Gas content decreases with increasing water content, but not to so low a value as persists in puddled soils, indicating that some of the occluded pores retain gas



1. Seasonal changes in pH, Eh, and some physical properties of plowed layers of clay loamy brown lowland rice soIL. Flooding and puddling, 31 May; draining, 22 Sep 1966 (21).

during flooding. When the soil is drained, the resulting oxidation helps restore soil structure. These seasonal changes in soil structure are more pronounced close to the soil surface (12).

Aggregate degradation under reducing conditions is caused by the decomposition of cementing agents or by changes into sols and ions. Flocculation occurs when cementing agents change to flocculating agents.

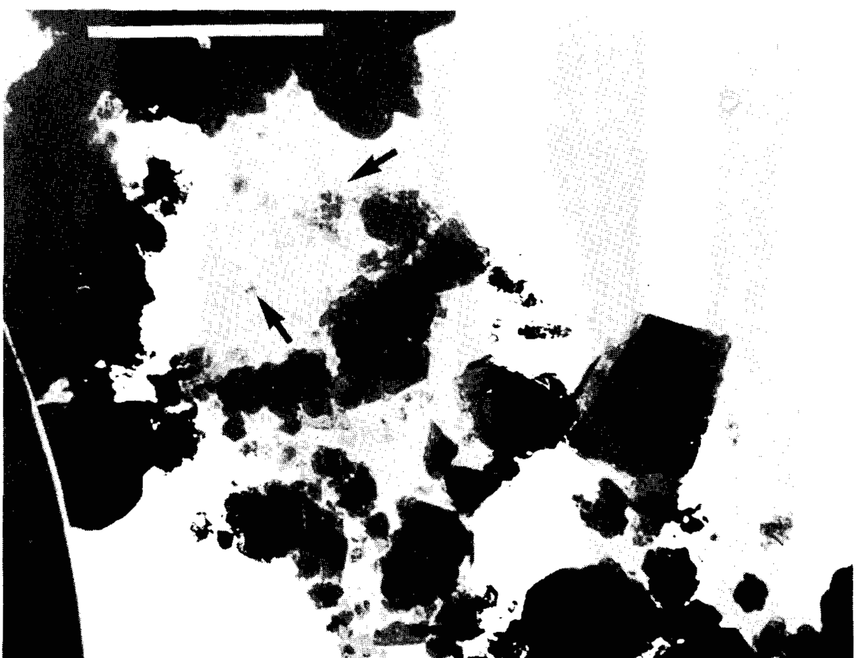
Concentrations of 0.2M HC1 soluble Fe and Al, the primary flocculating agents, increase as reduction proceeds (26). Flocs from reduced soils easily react with o-phenanthrolin or aluminon and form red colorations (25). These findings suggest that Fe and A1 cementing agents become more reactive in reduced soils where ferrous ions dominate.

When dispersion ratio is measured in water in contact with air, some of the ferrous ions oxidize, hydrolyze to ferric hydroxide, and become polynuclear hydroxoiron complexes (29) that act as flocculating agents (2). Soils reduced and shaken in water in oxygen-free conditions were qualitatively confirmed to flocculate.

Saito and Kawaguchi (25) observed soil flocs with a microscope to study flocculation mechanisms. Amorphous material that was locally and irregularly absorbed by the surface of clay particles bound them into a fibrous network (Fig. 2). In rice soils derived from Andosols, fibrous, microaggregated allophanes were observed, as were microorganisms (Fig. 3) and their metabolic products. The latter are thought to have little effect on flocculation under reducing conditions. Many 0.1-mm-diameter flocs formed extended networks (Fig. 4). Coarse sand or silt particles with active parts that react with finer particles and their flocs became components of the flocs (Fig. 5).

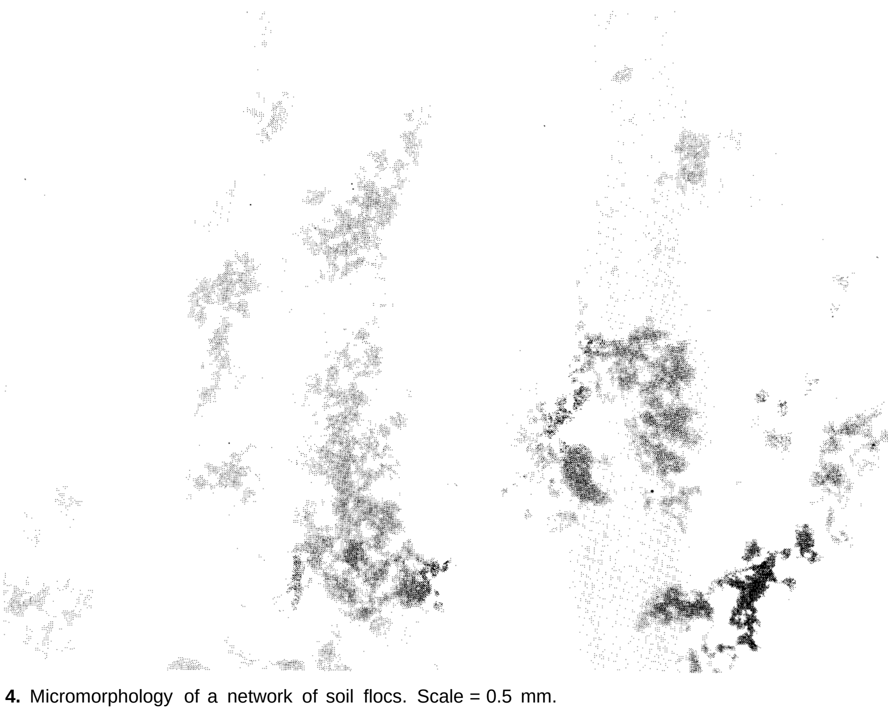
When soil samples were reduced by flooding, those samples taken from wet fields were flocculated. Those samples that were air-dried before flooding were fairly well dispersed (26). Air-drying before flooding increases the content of water-soluble, readily decomposable, organic matter, which is thought to inhibit the action of flocculating agents. The effect is similar to that of flocculated kaolinite dispersed by aqueous leaf extracts (3).

Gley soils also flocculate because they are reduced even after drainage (23). However, the poor flocculation sometimes observed is attributed to excess water-soluble and readily decomposable organic matter. Gley soils have jelly-like massive peds with low bulk density and large, primarily

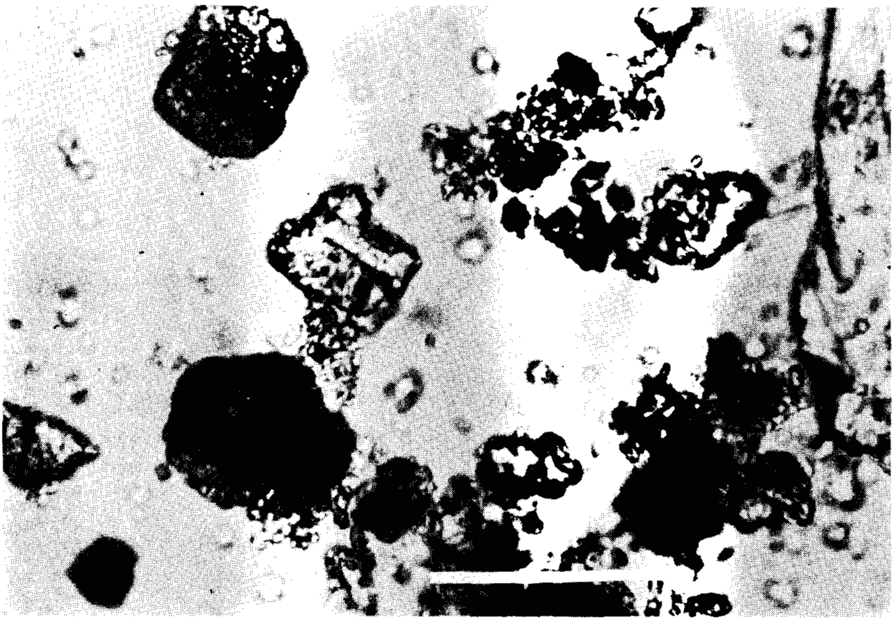


2. Micromorphology of soil flocs of a brown lowland soil. Scale = 2 µm.

3. Micromorphology of soil flocs – fibrous and aggregate allophane in rice soil derived from an Andosol. Scale = 2 μm. Notice the bacteria absorbed on the aggregated allophane.



4. Micromorphology of a network of soil flocs. Scale = 0.5 mm.



5. Micromorphology of soil flocs binding sand grains. Scale = 0.05 mm.

water-filled, pores. There is a slight seasonal fluctuation in the three-phase distribution through the horizons.

Flocculation of reduced soils explains the gradually lessening permeability in well-drained rice soils after flooding and puddling (16, 18). It explains also the high water holding capacity (27), and very low permeability of gley soils, despite their high porosity (19).

Morphological features

In the plowed layer of rice soils that are alternately flooded and drained, few peds develop, but those that develop are peculiar to rice fields.

Six types of peds are observed in drained, puddled systems: massive, single-grained, blocky, granular, porous, and open. Porous and open peds are specific to rice soils (1).

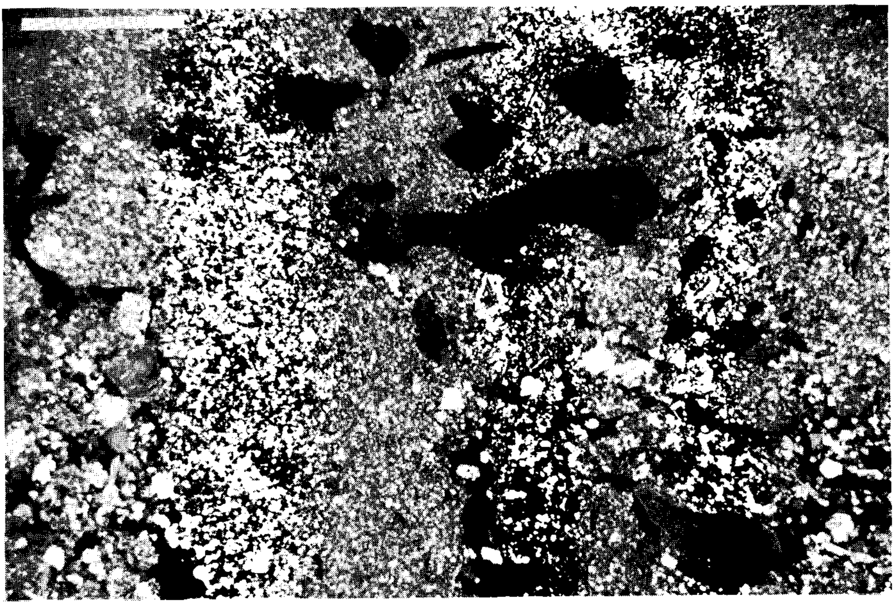
In the plowed layer, three subhorizons generally can be recognized on the basis of ped arrangement. The first has massive peds and the third has massive or weakly blocky peds. The second subhorizon is determined by texture, clay minerals, applied organic matter, and puddling intensity (1), and is influenced by field topography and climate. This ped classification combines characterizations based on aggregates with those based on pores. Porous and open peds are massive with pores of unusual shape and size.

For the plowed-soil layer considered in Figure 1, descriptions (24) of the subhorizons were prepared following macro- and microscopic observation. Typical micromorphology of drained soils is shown in Figures 6, 7, and 8 and that of a flooded soil in Figure 9.

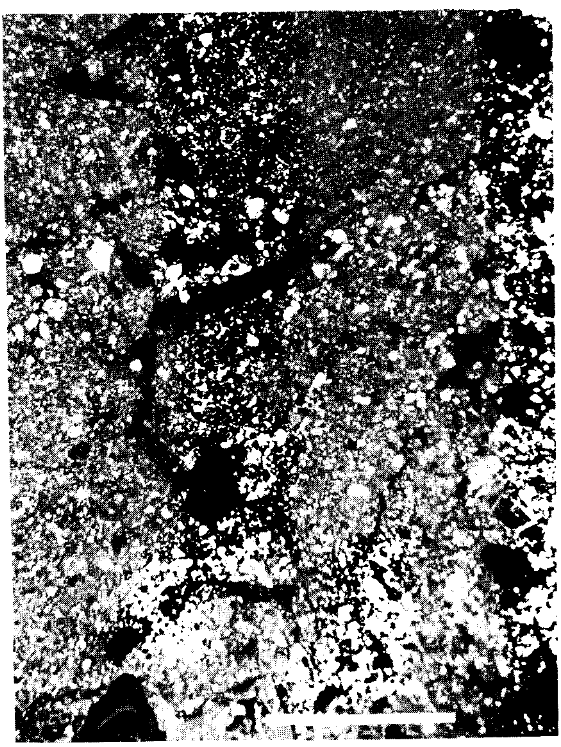
Figure 6 shows the top, 15-mm deep, massive subhorizon of fine particles differentiated by puddling, and the second, thin subhorizon of single, sand grains. Because of the dense soil suspension caused by puddling, no differentiation occurred in the third massive subhorizon.

Pores created by gas evolved during flooding persist in the dried soil (Fig. 7) because of the fine texture and flocculation under reducing conditions. Soil around cracks, pores, and the single-grained subhorizon oxidized and dehydrated more rapidly after draining. Weak aggregation occurred around the single-grained subhorizon (Fig. 8).

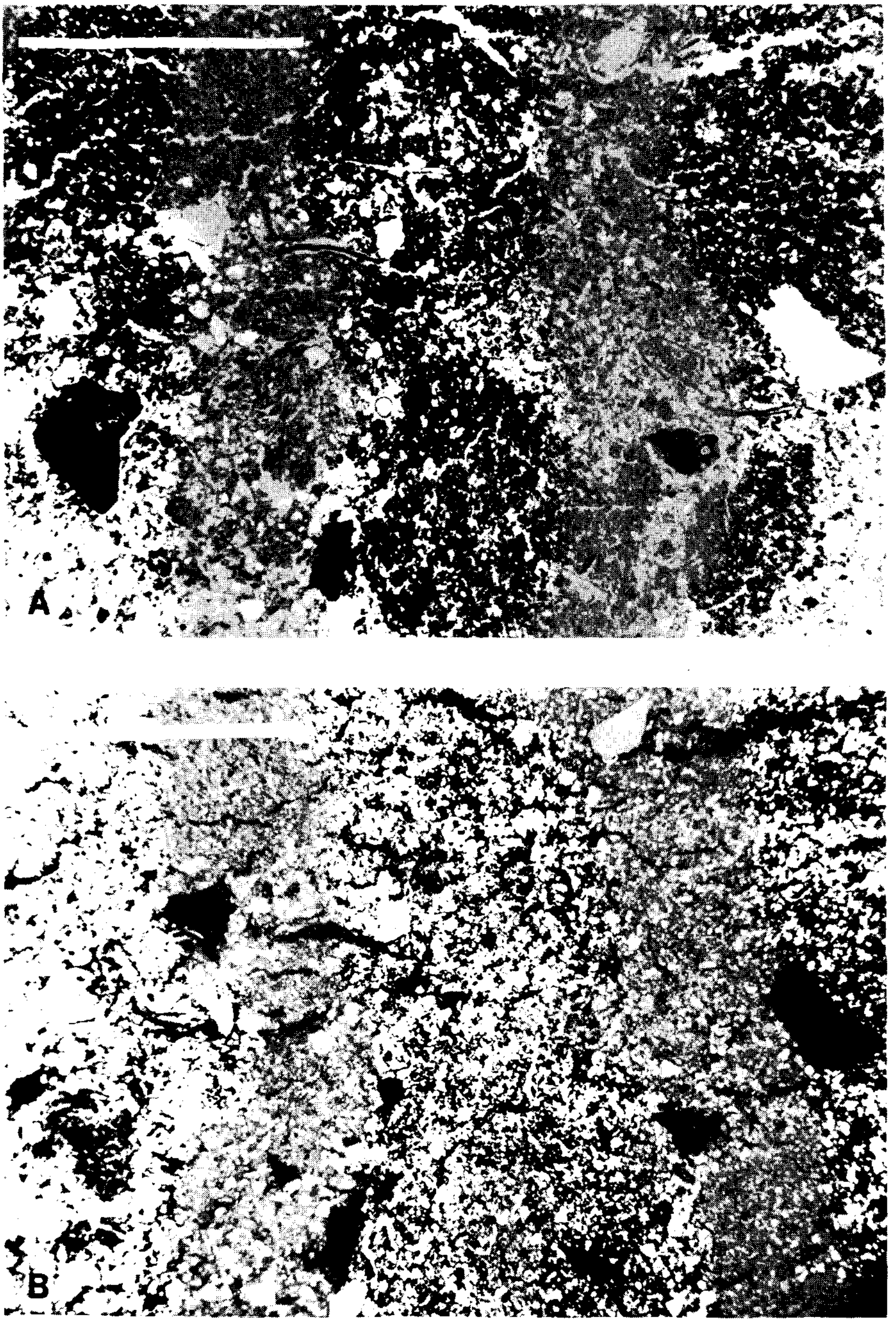
6. Top massive and thin single-grained subhorizons. Oriented specimen under polarized light. Scale = 5 mm.



7. Pores created by gas evolved in the reduction process. Oriented specimen under polarized light. Scale = 5 mm.



8. Weak aggregation around a single-grained subhorizon. Oriented specimen under polarized light. Scale = 5 mm.



9. Micromorphology under flooding. Oriented specimen a) under plain light, b) under polarized light. Scale = 5 mm. Fine laminar pores were formed by freeze-drying the moist sample to avoid shrinkage prior to resin fixation.

Soil under reducing conditions is macroscopically massive because the existing aggregates are embedded in muddy substances that developed from aggregate degradation during puddling and reduction.

Subhorizons and aggregates also were microscopically examined. Figure 9 shows two types of aggregate in the single-grained subhorizon. The larger degrade into massive and single-grained subhorizons. There are few pores (right side of Fig. 9), except for pores created by gas evolution. Similar pores only are found in the third subhorizon and in gley soils.

Typical peds are massive under flooding, but regenerate during drying. Massive or weakly blocky peds are common, and granular peds are found in soils where much organic matter has been applied and rice productivity has been high (4, 13, 29). Those peds appear to be a complex of two structural types: one reaggregates from mud after draining, and one remains degraded under reducing conditions because of high stability in water.

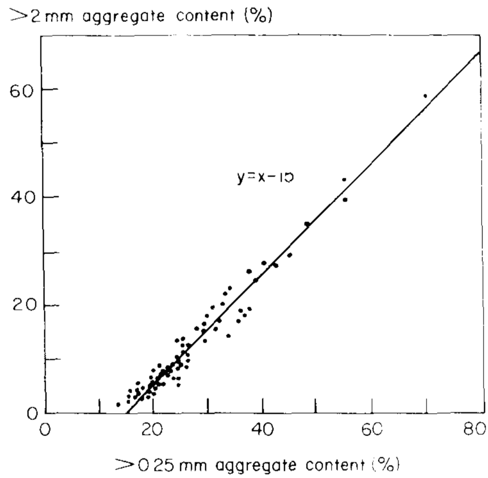
Granular peds do not necessarily favor rice cultivation. Soil structure-ricegrowth relations depend on degree of percolation, soil fertility, tillage (4, 13), and climate (6).

Water-stable aggregates

Performing an aggregate analysis on reduced soils is difficult. Because of its jelly-likemassive state, a wet-sieved clod remains on the net of the sieve with little disintegration (15). The clod must be crushed into 10- to 15-mmparticles, and fine clods need to be shaken in water before sieving (12).

For the soil considered in Figure 1, which was massive to weakly blocky after draining, the aggregate size relationship of Figure 10 was obtained (22). The linear correlation between the two sizes of aggregates is statistically significant. The intercept on the horizontal axis is close to the content (9.5%) of primary particles larger than 0.25 mm. Thus, wet clods, whether from flooded or drained soils, are gradually destroyed when shaken in water. True aggregates were not obtained, which suggests that aggregate content is only an index of the strength of interparticle bonds.

Several scientists have studied the water-slakingof air-dried samples of drained rice soils. Aggregates from granular soil had higher water stability than those from



10. Correlation between contents of aggregates larger than 2 mm and those larger than 0.25 mm.

massive to blocky soils (13), and from fertile soils higher than from less fertile (10).

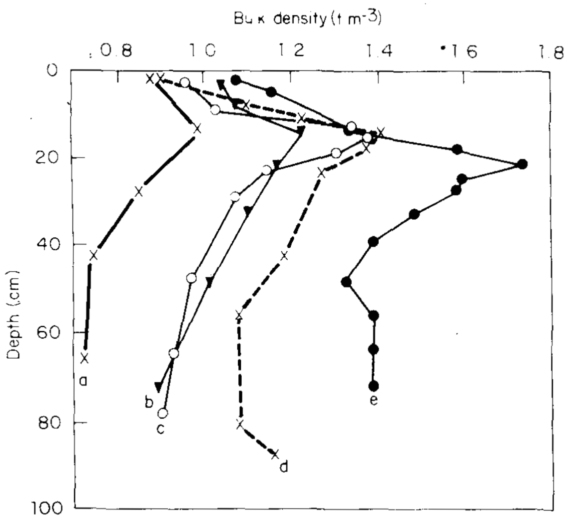
In massive to blocky soils, cementing agents concentrate in different-sized water-stable aggregates (7, 9, 10, 11, 30). Generally, organic matter, Fe, Mn, and clay content and C:N ratio increase with aggregate size. Concentration seems to occur during drying because flocculating agents change into cementing agents during oxidation, One may cite in support that aggregation of air-dried soil samples under reducing conditions is similar to that under oxidizing conditions (22). Formation of water-stable aggregates, and their stability against puddling and reducing conditions, is not well understood.

SUBSOIL STRUCTURE

Cultivation of rice soils changes subsoil and plow-layer structure. Particularly susceptible to change are drained polder soils (gleys) (8) -- where a series of soils with different ages after reclamation forms a hydrochronosequence -- and well-drained, brown lowland soils (16, 17).

Polder soils

In polder soils, puddling, and alternate flooding and draining during rice cultivation greatly modify soil structure (8), and do not favor ripening. A distinct plowpan without



11. Bulk density curves for rice cultivation in Kojima Polder, Japan (8). Age after reclamation, rice yield, and texture are as follows: a = 14 yr (8 yr rice, 4.5 t ha^{-1}, silty clay; b = 43 yr, 5.1 t ha^{-1}, clay to silty clay; c = 130 yr, 4.8 t ha^{-1}, silty clay; d = 240 yr 4.5 t ha^{-1}, clay; e = 300 yr, 4.2 t ha^{-1}, sandy loam to loam.

illuviated Fe and Mn oxides begins to form immediately below the plowed layer. Over time, as after 8 yr of rice cultivation (Fig. 11), prismatic peds develop in the horizons below the plowpan.

Those peds permit percolation that favor rice growth when there is a less-developedplowpan. Soil horizons differentiate as the peds develop. The plowpan hardens as Fe and Mn oxides leach from the plowed layer and deepens as the illuvial horizon falls. The plowpan inhibits root growth and percolation, and reduces rice productivity.

Brown lowland soils

Mitsuchi (16, 17) studied structural changes caused by rice cultivation in brown lowland soil where subsoils became gray and dense-blocky or prismatic as a result of alternate flooding and draining. Adjacent soils under nonirrigated cultivation remained brown and massive or weakly blocky.

On soils of lower inherent permeability, the subsoil extends deeper and a distinct plowpan forms. It forms most easily in loam soils. Table 1 shows that, compared to an adjacent area cropped with vegetables, rice cultivation increased bulk density, decreased macropores, and lessened conductivity in the 0- to 53-cmlayer. The upper horizons stayed wet.

Table 1. Changes in the physical properties of loamy brown lowland soils after 52 yr rice cultivation (17), 27 Oct 1981.

Crop	Rice							Vegetable			
Horizon	Apg	Ag_2	Bg_2ir	Bg_2	Bg_3mn	C_1	C_2	Ap	C_1	C_2	C_3
Depth (cm)	0-10	10-19	19-25	25-36	36-53	53-84	84-100+	0-23	23-35	35-65	65-100+
Bulk density ($t\ m^{-3}$)	1.17	1.37	1.37	1.29	1.26	1.24	1.11	1.08	1.13	1.07	1.09
Three-phase distribution (vol %)											
Solid	44.3	51.3	50.6	47.2	45.7	43.9	39.3	39.1	40.0	37.7	38.3
Liquid	51.3	46.3	43.5	39.8	34.6	27.1	36.6	26.3	26.3	26.3	33.7
Gas	4.4	2.4	5.9	13.0	19.7	29.0	24.1	34.6	33.7	36.0	28.0
Pore distribution (vol %)											
Large (<pF2)	5.2	2.2	5.9	16.0	22.4	23.6	21.3	23.0	22.2	25.8	23.3
Medium (pF2-3.9)	31.8	25.3	22.0	16.8	16.9	21.1	26.2	25.4	26.4	24.7	26.7
Fine (>pF3.9)	18.7	21.2	21.5	20.0	15.0	11.4	13.2	12.5	11.4	11.8	11.7
k_{20} ($\times 10^{-5}$ cm s^{-1})	2.0	1.2	3.5	5.0	160	200	250	400	570	380	210

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SOIL MECHANICS IN RELATION TO TILLAGE, IMPLEMENTS, AND ROOT PENETRATION IN LOWLAND SOILS

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Abstract

Basic soil mechanical properties are considered in terms of principal stresses and critical state soil mechanics. The recent hydraulic history of a soil and its present soil water content influence its mechanical behavior.

Soil mechanical properties that affect penetrometers are described in some detail, and the forces and pressures that affect tillage implements and elongating root tips are discussed. Mechanical factors that influence the ability of roots to penetrate hardpans are examined.

SOIL MECHANICS IN RELATION TO TILLAGE, IMPLEMENTS, AND ROOT PENETRATION IN LOWLAND SOILS

STRESSES AND STRAINS

Soil mechanical properties are very complex. They differ greatly between soils and also for the same soil at different water contents. Mechanical properties relate stress (force/unit area) to strain (deformation or change in shape or size) of a volume of soil.

Stresses can be described in several ways, but the most consistent way is to use principal stresses. Principal stresses arise because at any point in a volume of soil that is subjected to any system of external or internal stresses there exist three mutually perpendicular planes on which the shear stresses are zero. The stresses acting normally on these planes are known as principal stresses, and are ranked $\sigma_1, > \sigma_2, > \sigma_3,$ where $\sigma_1, \sigma_2,$ and σ_3 are the major, intermediate, and minor principal stresses.

A Mohr circle gives the value of the shear stress acting in any direction relative to the principal stress axes. The maximum shear stress acting in a medium is given by the radius of the Mohr circle:

$$\sigma_{max} = (\sigma_1 - \sigma_3)/2 \qquad (1)$$

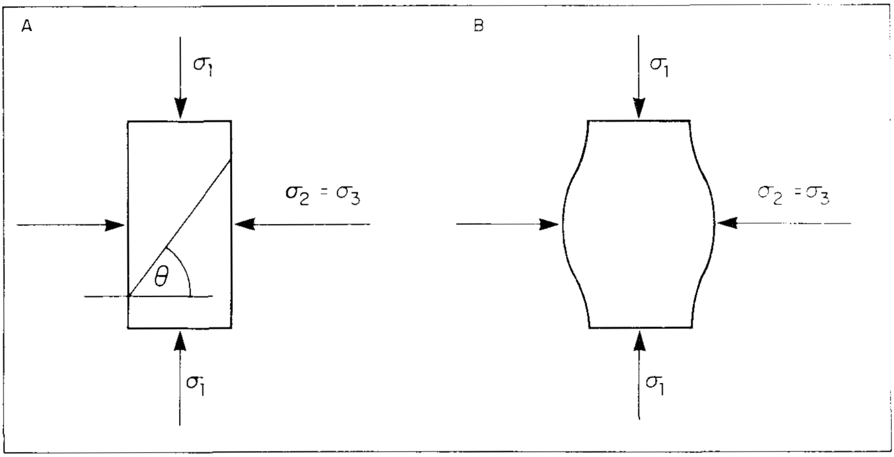
The mean compressive stress or pressure is

$$P = (\sigma_1 + \sigma_2 + \sigma_3)/3 \qquad (2)$$

At depth z, the weight of overlying soil contributes an overburden pressure γgz, to P, where γ is the density of the wet soil. In swelling soils, part of the pressure constitutes the overburden component Ω of the water potential(33).

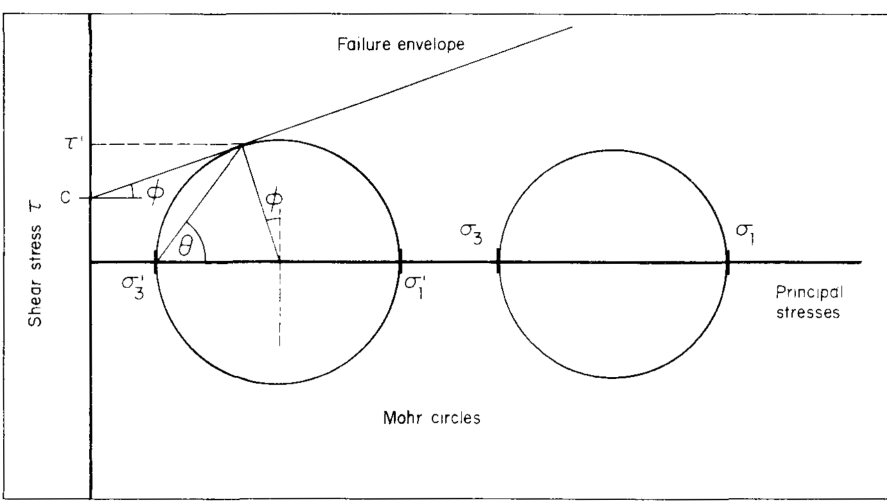
SHEAR STRENGTH

The shear strength of a soil is the value of the shear stress at which that soil fails by shear. Shear strength can be determined using a triaxial cell apparatus in which σ_2 and σ_3 are equal and usually are set to some arbitrary value and σ_1 is increased until the soil fails (21). Primed values (e.g. σ_1') indicate stress values at failure. The angle of



1. Soil failure under a system of principal stresses. A. Brittle failure along a shear plane at angle q. B. Plastic failure throughout the sample.

the failure plane, q = (p/4 + f/2), is shown in Figure 1A, where f is the angle of internal friction of the soil. Failure occurs when the Mohr circle touches the failure envelope (Fig. 2). As a result of internal friction, the shear strength t' is slightly less than t_{max} for f > 0. The failure envelope can be identified by producing a set of Mohr circles with various $s'_2 = s'_3$ and s'_1. The slope of the failure envelope is tan f and its intercept C is the shear cohesion of the soil.



2. Mohr circles giving shear stress at any angle q relative to the principal stress axes. Shear failure occurs when the Mohr circle touches the failure envelope.

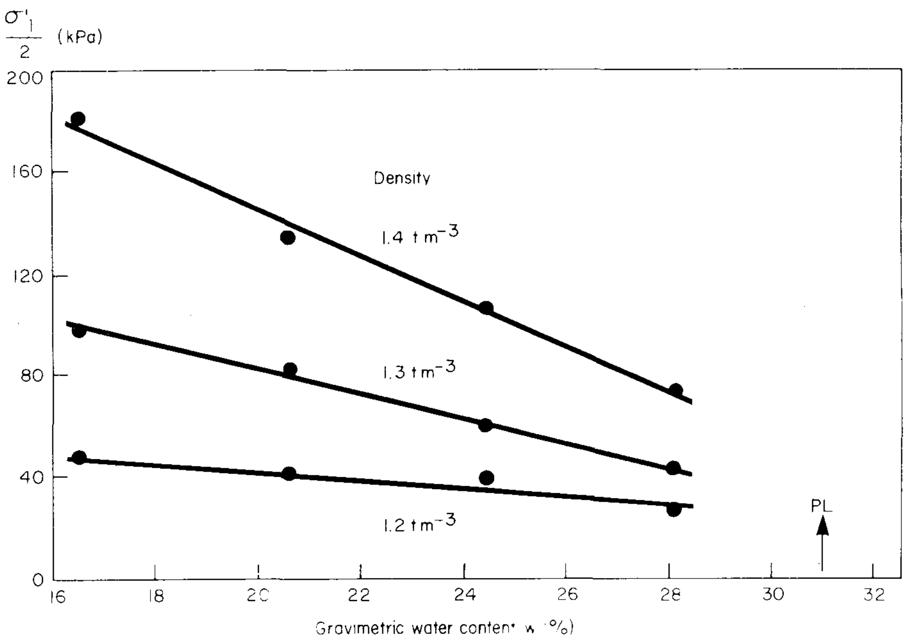
A simpler, quicker method to estimate C is the unconfined compression test, in which a cylinder of soil is loaded to failure by a stress σ_1' on its ends with $\sigma_2' = \sigma_3' = 0$. This gives

$$C = \sigma_1'/(2\ \tan[\pi/4 + \phi/2]) \qquad (3)$$

which can be used to estimate C if ϕ is known. Values of f range from 0° for saturated clays to 45° for sands. In moist conditions, soils with intermediate textures, such as silts and loams, often have values ϕ = 35–40°. Shear strength usually decreases sharply as soil–water content increases (Fig. 3).

COMPRESSIVE STRENGTH

Soil response to compression also can be investigated using a triaxial cell. The external pressure $P = \sigma_1 = \sigma_2 = \sigma_3$ is varied and changes in volume of the soil sample are measured. Test soils usually are fully drained to allow pore



3. Effect of water content and density on maximum shear stress at failure ($s_1'/2$) in unconfined compression tests (27).

fluids (air and/or water) to escape. Results can be expressed in terms of the voids ratio e of the sample:

$$e = V_e/V_s \tag{4}$$

where V_e is the volume of pores and V_s is the volume of solid particles. The voids ratio is related to porosity and specific volume ν by

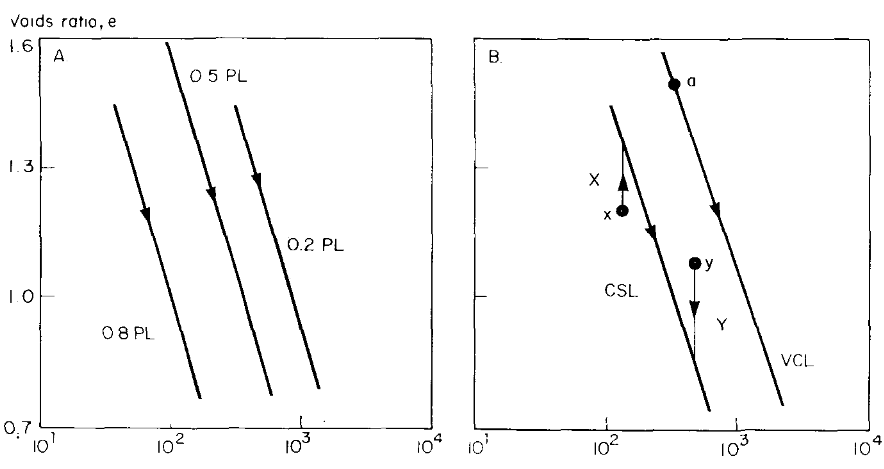
$$\eta = e/(1+e), \text{ and } \nu = (1+e)/\rho_s \tag{5}$$

where ρ_s is the density of the solid particles.

If the soil is loose, then a plot of e against $\log_e P$ is called the virgin compression line (VCL). Examples are given in Figure 4AB. The relationship is:

$$e = e_a - \log_e(P/P_a), \tag{6}$$

where the suffix a refers to some reference point a. The parameter is a measure of soil compressibility. Soil cannot exist in states to the right of VCL in Figure 4B. VCL varies with water content (Fig. 4A).



4. Response of soil to isotropic stress: A. At different water contents (as fraction of plastic limit water content) for a loam (25% clay). B. Without shearing (VCL) and with continuous shearing (CSL). PL = plastic limit.

ELASTIC DEFORMATIONS

For small stresses, straining may be elastic and reversible, and the strain energy may be recoverable. For example, with small shear stresses, removing the stress may allow the sample to regain its original shape. In this elastic region, the stress:strain ratio is called the shear modulus G of the soil. Similarly, applying small stresses in the unconfined compression test enables the uniaxial or Young's modulus E to be determined.

$$G \cong E/3 \tag{7}$$

Similarly, a bulk modulus may be defined for small isotropic stresses P. For soils, the response is not perfectly linear and there is some hysteresis. Farrell and Greacen (6) gave E values from 5 to 25 MPa, depending on soil water content and density. Such values were of order 10^3 x the shear cohesion C of their molded soil samples.

TENSILE STRENGTH

Tensile failure can occur when s_3 is negative. Tensile failure results in the cracking of soil when it dries, and in the fragmentation of dry or brittle soil during tillage. Tensile strength is measured by the indirect tension, or Brazilian, test. In the indirect tension test, a cylinder of soil of length L and diameter D is loaded across a diameter by a force F (Fig. 5). Elastic straining causes tensile stress $T = s_3$ in the center of the cylinder at right angles to the direction of application of F. F is increased until T = Y, where Y is the tensile strength of the soil, and the sample breaks into two parts. Tensile strength is given by:

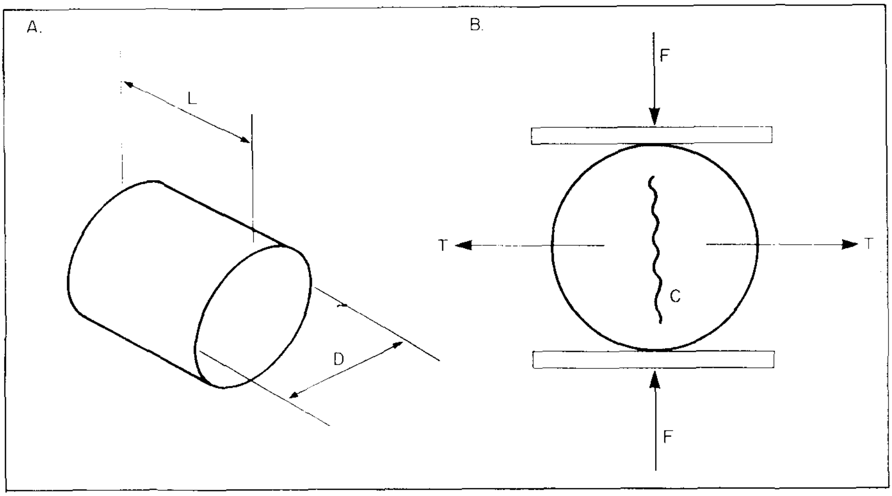
$$Y = (2F'/\pi DL)\ g(x) \tag{8}$$

where g(x) accounts (7) for any flattening along the lines of application of F. For negligible flattening, g(x) = 1.

For spherical aggregates of diameter D, the same reasoning applies, and

$$Y = \sigma_2' = \sigma_3' = 0.576(F'/D^2)\ h(x). \tag{9}$$

Methods for determining Y for aggregates were discussed by Dexter and Kroesbergen (4).



5. A. Soil cylinder for Brazilian test. B. Force F applied to a sphere or cylinder creates a tensile stress T which can cause a crack, C.

Tensile strength is a sensitive measure of soil structural condition because it responds to microcracks within the soil mass that usually are closed and inactive under the positive stress conditions that occur in triaxial and penetrometer tests. This sensitivity prompted the development of a measure of soil friability k. Friability is "the tendency of a mass of unconfined soil to break down and crumble under applied stress into a particular size range of smaller fragments" (37). Friability is

$$k = -d\log_e Y/d\log_e V, \qquad (10)$$

where $V = \pi D^3/6$ is the aggregate volume, k = 0 for a nonfriable, classical soil, and k = 0.4 for a very friable soil.

CRITICAL STATE SOIL MECHANICS

If soil is continuously sheared or molded while it is compressed, it will follow a different but equally well-defined line, known as the Critical State Line (CSL) (Fig. 4B). Critical State Soil Mechanics aims to predict the shear and volumetric strains produced in soil by combinations of imposed stresses. The Critical State theory was outlined by Kurtay and Reece (23) and Hettiaratchi and O'Callaghan (16).

Soil in states to the left of CSL in Figure 4B is brittle, and soil in states between CSL and VCL is plastic.

Brittle soil tends to deform with a well-defined shear plane (Fig. 1A), and plastic soil tends to deform uniformly (Fig. 1B).

When soil is deformed or sheared, its voids ratio e changes in the shear zone until it lies on the CSL appropriate to its water content. and the acting stress level P. In dense soil, a shear plane forms. It may be only 10 particle diameters across. Within that shear zone the soil becomes less dense (path X in Fig. 4B) and hence weaker. Therefore, shearing continues along the initial shear plane, and the bulk of the soil is unaffected. With loose soil, shearing increases density (path Y in Fig. 4B). The sheared zone is then stronger than the bulk of the soil, and shearing moves to another shear plane. This process continues until shearing has occurred throughout the soil volume and the new, denser state is uniform.

These reasons explain why it is easy to compact, but difficult to loosen, a soil uniformly. The principal mechanisms for uniform soil loosening are molding or repeated shearing in different directions at low stress levels P and natural processes such as wetting and drying cycles (15).

RESISTANCE TO PENETRATION

Penetrometers measure soil strength rapidly. A standard probe for field use is conical (Fig. 6A) with semiangle $a = 15°$ and maximum diameter, $D_P = 20.27$ mm. A common design for laboratory studies of root penetration has $a = 30°$ and $D_P = 1.00$ mm. Readings from the two types of penetrometers cannot be equated because there are effects of D_P (40) and a (22). Penetrometer readings are best taken at depths $z > 4D_P$, where soil surface effects are negligible.

Results usually are given as the penetrometer pressure

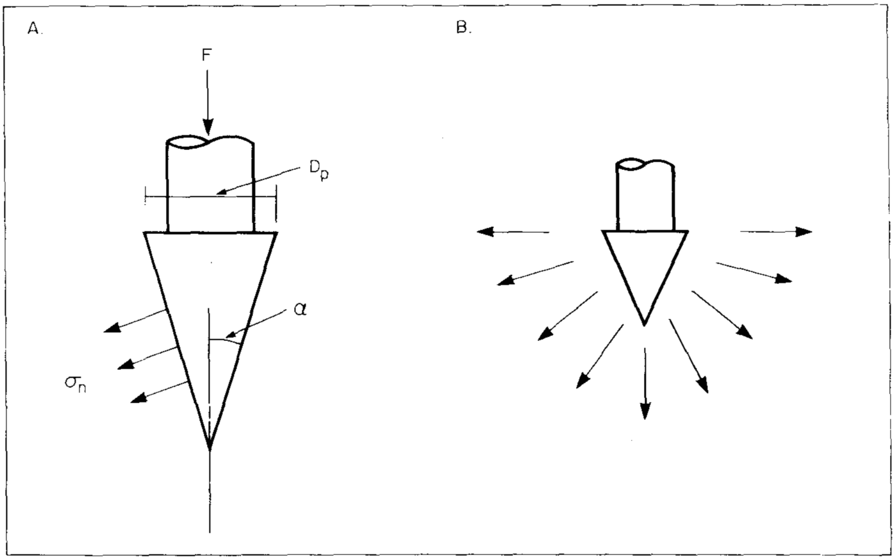
$$q_p = 4F/\pi D_p^2 \qquad (11)$$

The pressure that the penetrometer exerts on the soil (Fig. 6A) is given by

$$\sigma_n = q_p/(1 + \tan\delta \cot\sigma), \qquad (12)$$

where d is the angle of soi1:probe friction.

Penetrometers with large a and finite d tend to compress the soil ahead of them (13). Observations of soil par-



6. Penetrometers. A. Force F produces normal stress s_n on soil. B. Spherical mode of soil displacement.

ticle movement indicate that soil strain around a penetrometer tip is spherical (Fig. 6B). Therefore, the pressure s_n on the penetrometer surface has been equated with the pressure required to expand a spherical cavity in soil. This problem was considered by Greacen et al (13) and Vesic (39). The main concept is that plastic strain or failure occurs around the penetrometer out to some radius R, which depends on soil compressibility, and that beyond R elastic straining occurs. The pressure P_U required to expand a cavity is given by Vesic:

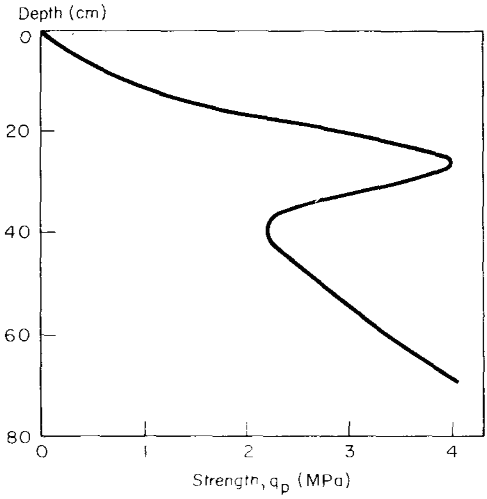
$$P_u = CQ_c + PQ_q \tag{13}$$

where C is shear cohesion and P is isotropic stress in the soil (Eq. 2) before penetration. Q_c and Q_q are dimensionless spherical cavity expansion factors. For an incompressible (l = 0), frictionless (f = 0) soil such as a saturated clay undergoing rapid straining, $Q_q = 1$, and

$$Q_c = (4/3)[10g_e(G/t') + 1] \tag{14}$$

where t' is the shear strength (Fig. 2) and G is the shear modulus (Eq. 7).

Figure 7 is an example of a strength profile of a rice soil obtained with a penetrometer (43). The main limitation



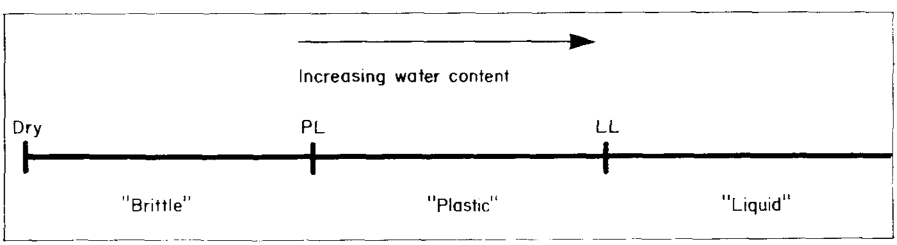
7. Penetrometer strength, q_p, as a function of depth, for plot F12 (40% clay), IRRI, Jun 1983 (43).

of penetrometers is that the same q_p value can be obtained from a wide combination of soil properties C, ϕ , G, λ . Therefore, penetrometer readings must be carefully interpreted. Some other problems associated with penetrometers were discussed by Mulqueen et al (25).

EFFECTS OF SOIL-WATER CONTENT

The Atterberg limits provide reference water contents at which freshly molded soil has defined mechanical properties. The plastic limit, PL, marks the transition between brittle and plastic consistency. The liquid limit, LL, marks the transition between plastic and liquid consistency (Fig. 8). There are standard methods for determining PL and LL (2).

In some soils, a gravimetric water content near w = 0.9 PL provides maximum friability (37). Tillage at this optimum water content maximizes the proportion of small aggregates (26).



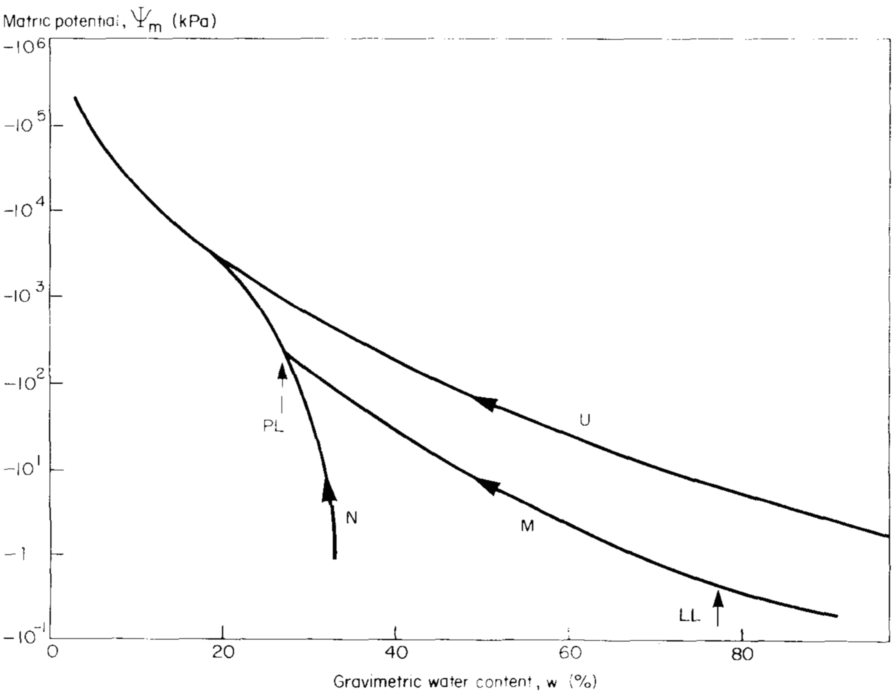
8. Changes in soil consistency with increasing water content.

The matric potential Y_m of the pore water affects the soil stress system and hence soil strength. Y_m is negative in unsaturated soil and tends to pull soil particles togeth – er. A negative Y_m is therefore equivalent to a positive ex – ternal pressure on a soil sample. In unsaturated soil, Y_m only acts on some of the internal surfaces and only part, f, of Y_m is effective; f varies from 0 in dry soil to 1 in saturated soil. Intermediate values of f were considered by Greacen (11) and Towner and Childs (36). The total effective principal stresses within a soil volume therefore are

$$\sigma_i^e = \sigma_i - f\Psi_m \quad (15)$$

for i = 1, 2, 3.

Croney and Coleman (3) studied the drying of saturated, puddled clays (Fig. 9). The water characteristic of the



9. Matric potential- water content curves for drying of a heavy clay soil in its natural state, N; after being puddled and allowed to dry with no further disturbance, U; or with continuous disturbance, M (3).

drying material was on curve U for the undisturbed puddled clay and on curve M when the clay was disturbed during drying. Curve M met, at PL, the water characteristic curve N of the natural (nonpuddled) soil. PL was close to the air-entry point and the start of the residual shrinkage region. Curves U and M are exactly analogous to the VCL and CSL of Figure 4B, except that the stress is imposed internally by the water matric potential instead of by external mechanical stress.

Greacen (10) showed there is an approximate linear relation between $\log_e(-\psi_m)$ and w in the range PL to LL, and that for several soils $\psi_m \approx -65$ kPa at PL, and $\psi_m \approx -1$ kPa at LL. Thus, the effective stress P'_e in a continuously molded, shrinking clay at any water content w can be estimated as

$$\log_e (P'_e/\text{kPa}) = 4.19\ (\text{LL}-w)/(\text{LL}-\text{PL}) \qquad (16)$$

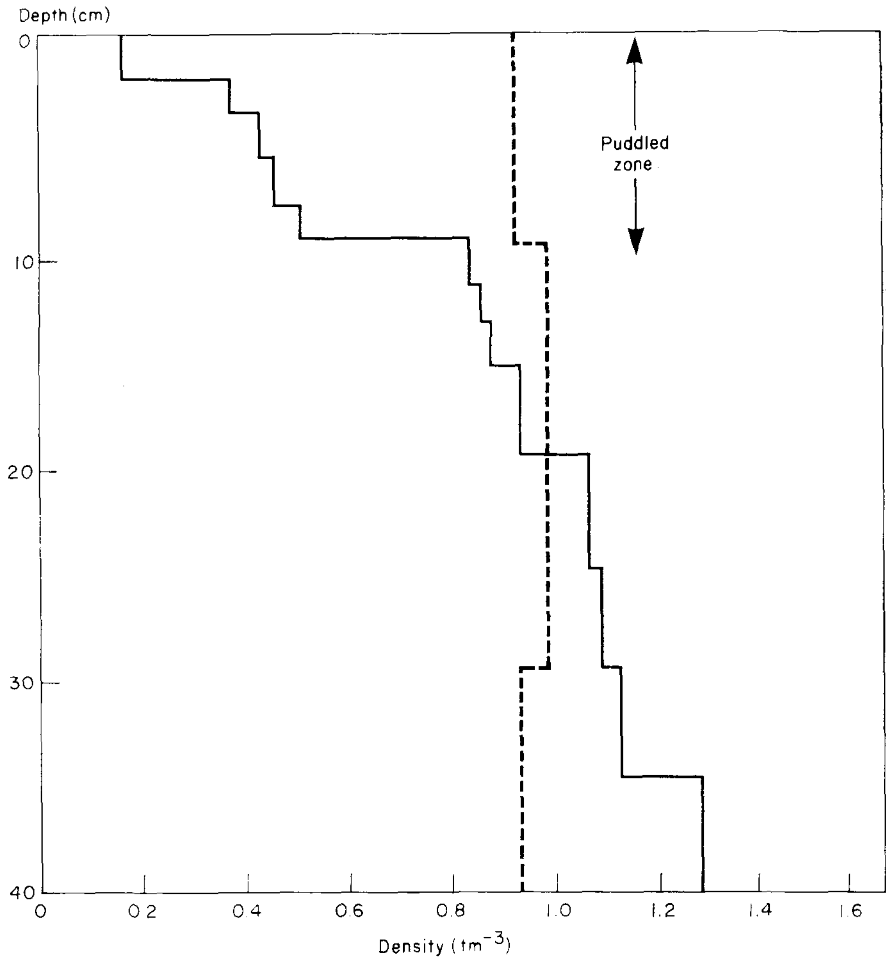
where P'_e is equivalent to the P of Eq. 2.

EFFECTS OF HYDRAULIC HISTORY

When a soil dries, it shrinks with a corresponding increase in bulk density. Figure 10 shows an example of this for a rice soil with 40% clay (43). As the soil shrinks, tensile stresses T are generated parallel to the soil surface. When T equals soil tensile strength Y, vertical cracking occurs. The cracks usually form hexagonal patterns on the surface. Their spacing depends on the ability of the soil to deform under stress: that is, on soil elasticity (24). A soil with a large elastic modulus will not readily deform and will form a more closely spaced crack pattern.

Water extraction by plants also causes soil to shrink and crack. Plant spacing can be varied to control crack spacings and widths in the field (20). Generally, the dense peds defined by shrinkage cracks are too large for structure generation by drying to be considered a useful tillage operation (44).

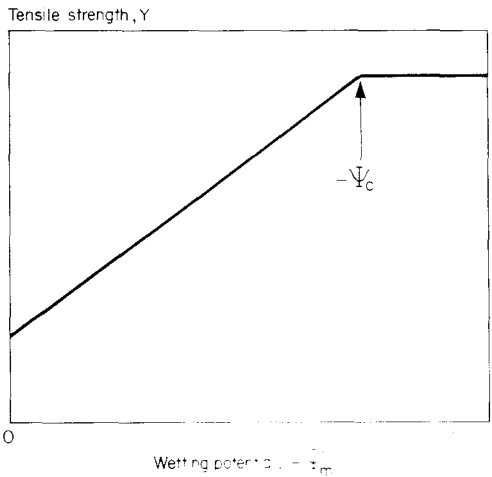
However, soil stresses generated during rapid wetting are important in soil structure regeneration. Dexter et a1 (5) showed that wetting artificial aggregates of about 10 mm diameter caused them to weaken or mellow (Fig. 11). Such reductions in Y depend on the wetting rate, which depends on wetting potential. If wetting potential is more negative



10. Profile of dry bulk density in puddled rice soill(–) and in dry soil after the rice crop (--) for plots F12 and F13, IRRI, 1983-84 (43, including personal communication, H. U. Neue).

than - Ψ_c, the critical mellowing potential, aggregates do not weaken; Ψ_c is –2 to –3 kPa. Weakening happens when closely spaced microcracks form during rapid wetting.

Sato (29) indicated that weakening through wetting operates only if the soil is initially drier than Ψ_m = -1 MPa, and that the effect is greatest if the soil is drier than –10 MPa. Sanchez (28) also found that puddled soil must be thoroughly dried before wetting and drying cycles will cause structural regeneration. The mellowing induced by wetting

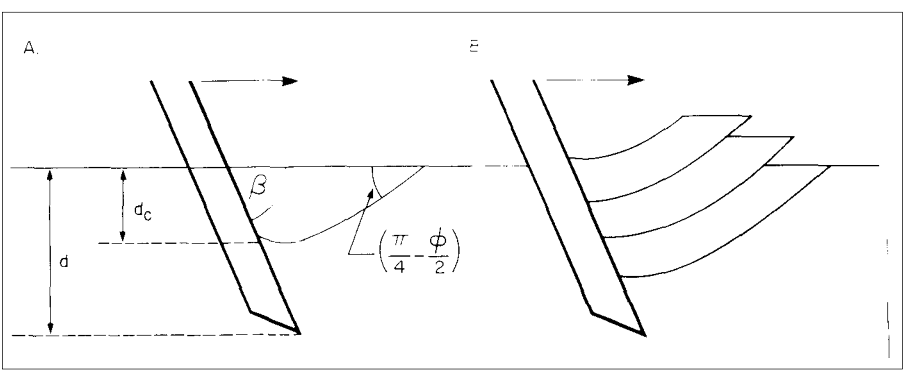


11. Reduction in tensile strength of dry soil aggregates caused by previous wetting from a wate source at potentials between 0 and y_c.

dry soil also increases friability (37) and soil fragmentation during tillage (38).

MECHANICS OF TILLAGE

Soil mechanics techniques can predict the draft force and the regions of soil disturbance produced by sloping, flat, narrow tines (9). A tine compresses the soil ahead of it until the stresses cause soil passive failure. Two basic types of failure occur at low implement speeds, depending on whether the depth is greater or less than a critical depth, d_c (Fig. 12A). Above d_c, failure depends on the presence of



12. Crescent failure produced by simple tines. A. Dimensions B. Successive blacks sheared off.

the soil free surface. Below d_c, the soil flows laterally around the tine. d_c depends on the rake–angle b but usually is comparable with tine width, b. Successive soil blocks shear off above d_c as the tine moves forward (Fig.12B). The spacing between the blocks depends on soil compressibility.

Applying plasticity theory to this problem is difficult, but the total horizontal draft force can be determined as the sum $F_H + F_h$ of the forces acting on the portions of the tine respectively above and below d_c. Hettiaratchi and Reece (17) presented a simplified method to calculate F_H as:

$$F_H = b(\gamma d_c^2 N_\alpha + C d_c N_c + C_a d_c N_a + q d_c N_q) \sin(\beta + \delta) \quad (17)$$

where g is the density of the wet soil, C_a is the adhesion between the soil and the tine, and q is the surcharge on the soil surface. Hettiaratchi and Reece present charts for rapidly determining the dimensionless N–factors. Stafford (31) pointed out that the cohesion (second) term in Eq. 17 usually accounts for 90% or more of F_H.

For depths below d_c, where lateral flow occurs:

$$F_h = bC(d-d_c)N'_c + bP_h(d-d_c)N'_q \quad (18)$$

where P_h is the effective horizontal pressure acting in the soil, and d is the tine working depth (Fig. 12A). Graphs of N'_c and N'_q as functions of f are given by Godwin and Spoor (9).

Speed dependence of draft force is caused by acceleration of the disturbed soil and speed dependence of some of the soil properties. Stafford (31, 32) noted a transition above ~3 ms^{-1} from crescent to flow failure. In crescent failure, shearing occurred along well–defined shear planes (Fig. 12) similar to those obtained with brittle failure in a triaxial cell (Fig. 1A) and associated with states to the left of CSL in Figure 4B. Flow failure occurred throughout the soil volume, as for plastic failure in a triaxial cell (Fig. 1B), and usually occurred between CSL and VCL in Figure 4B. The boundaries of the flow failure region were not clearly defined. Flow failure requires high speeds and energy inputs, but may apply in soil puddling that requires uniform energy dissipation throughout a soil volume (1).

Soil mechanics can predict draft forces and zones of soil disturbance for simple implements. More complex shapes cannot yet be treated analytically. Empirical studies still are necessary in such cases (e.g. 30). Soil mechanics cannot predict how the soil blocks produced by tillage shatter and crumble as they are pushed past and against each other by the implement. Soil structure after tillage probably depends more on the soil's initial mechanical, hydraulic, and micro–structural state than on the tillage implement.

MECHANICS OF ROOT GROWTH

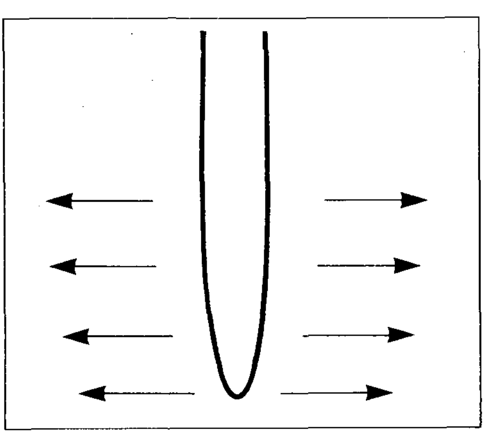
Internal and external stresses on a root must be balanced:

$$\Psi_i = \Psi_s + W + \sigma \qquad (19)$$

where ψ_i and ψ_s are the potentials of the water inside the roots and in the surrounding soil, W is an effective stress caused by tension in the cell walls, and s is the pressure exerted by the root against the surrounding soil and depends on soil strength. Roots can osmoregulate by modifying Ψ_i in response to changes in the right hand side of Eq. 19 by varying the content of osmotically active compounds, such as sucrose, in their cells, Greacen and Oh (14) observed corre–lations between ψ_i and soil strength.

Maximum axial growth pressures are around 1 MPa (35, 19); maximum radial growth pressures are around 0.5 MPa (8).

Roots tend to deform the soil radially (Fig. 13). The pressure required for that deformation can be considered as



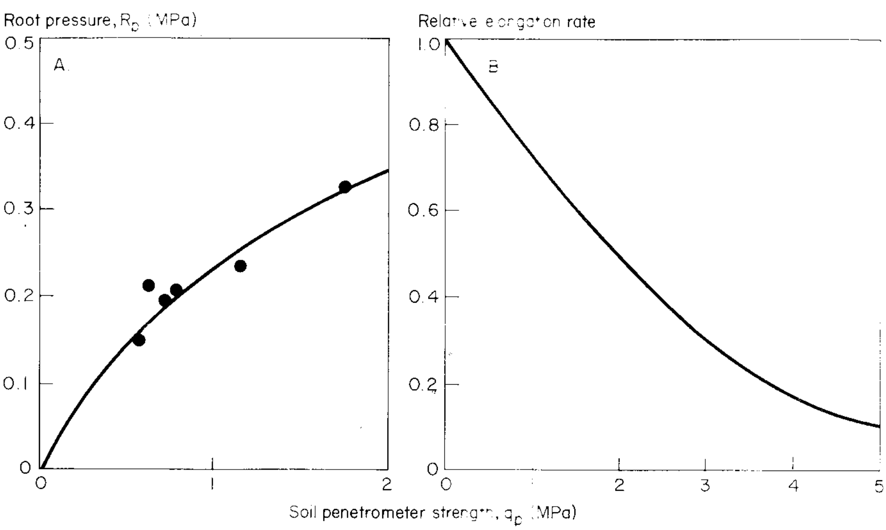
13. Cylindrical displacement of soil by an elongating root tip.

the pressure required to expand a cylindrical cavity (13, 39). The pressure is as given in Eq. 13 except that the factors are the dimensionless cylindrical cavity expansion factors, Q'_c and Q'_q. For incompressible ($\lambda = 0$) and frictionless ($f = 0$) soil, $Q'_q = 1$, and:

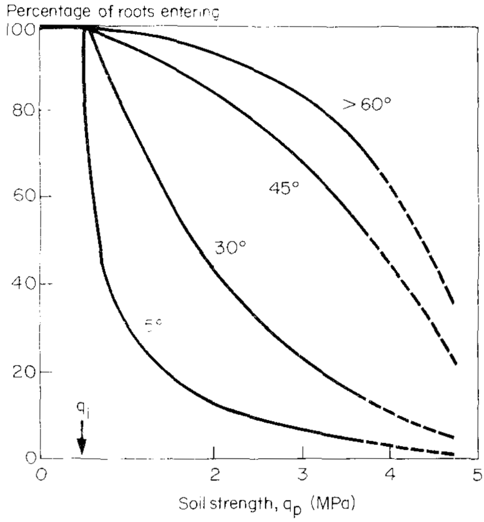
$$Q'_c = 1 + \log_e (G/\tau'). \quad (20)$$

For root growth, the rate of soil strain is low, and there is time for water drainage and consequent soil compression. This makes the assumptions of $\lambda = \phi = 0$ less applicable than for a penetrometer. Vesic (39) tabulated Q'_q and Q'_c for compressible, frictional soils.

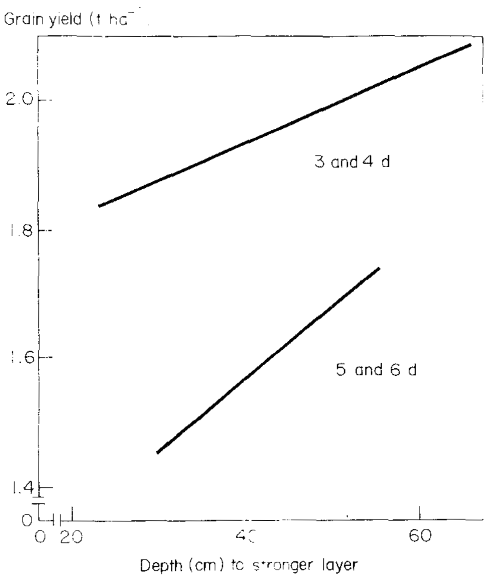
The differences in soil straining mode induced by roots and penetrometers and the fact that root:soil friction is less than penetrometer:soil friction together account for the differences between root and penetrometer penetration pressures (Fig. 14A). Effects of soil strength on root elongation rate have been measured by several researchers. Typical results are given in Figure 14B. Clearly, $q_p > 3$ MPa severely affects root elongation. Soil layers with $q_p > 3$ MPa have been noted in rice fields of several countries (Fig. 7 and J.C. O'Toole, personal communication).



14. A. Root penetration pressure (42). B. Relative elongation rate of peanut roots (34) as functions of soil strength, q_p.



15. Percentage of pea roots entering a block of soil of strength q_p which they encounter at various angles of incidence from soil of strength q_i (12).



16. Grain yield of mungbean as affected by depth to the stronger soil layer and by delay (d) between field-draining and seed-planting. IRRI Plot F13, 1984 (43).

A very important case is that of roots encountering a sharp soil discontinuity, such as a hardpan. The percentage of roots entering the pan depends on the angle of incidence of the root to the pan, and on the strengths of the pan and the overlying soil (Fig. 15). If the overlying soil is weak, then the roots may buckle more easily and be deflected along the top of the pan. In general, a root is deflected when its buckling strength (41) is less than the maximum growth pressure(18).

Limitation of root penetration by layers of high soil strength may account for the dependence (Fig. 16) on depth to such layers of the yield of mung bean at IRRI (43).

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TILLAGE IN LOWLAND RICE - BASED CROPPING SYSTEMS

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ABSTRACT

Seedbed requirements for rice and dryland crops are discussed in relation to soil physical properties. Puddling a clay soil with high percolation rate benefits rice growth but reduces the yield of following dryland crops because of soil structural deterioration, shrinkage, drought stress, and impeded root growth. If weeds are controlled, rice grows as well on unpuddled, low permeability soils as on puddled soil. Dry tillage and moderate drying are suitable for rice on heavy–textured, poorly drained, floodplain soils. Mechanical compaction may reduce percolation on a coarse–textured sandy soil more effectively than wet tillage. A tentative rating table is proposed as a tillage guide for lowland rice–based cropping systems.

TILLAGE IN LOWLAND RICE-BASED CROPPING SYSTEMS

Lowland rice culture is a sustainable system that has supported the high population density of Southeast Asia without causing the severe ecological imbalance and soil degradation problems that have limited intensive agricultural utilization of tropical uplands. There is, however, a pressing demand to increase productivity of rice-based cropping systems.

It is therefore important to identify soil and water management constraints to rice production and to develop technological systems to alleviate them. Food production from wetlands can increase substantially if technology facilitates multiple cropping. Wetland soil and water resources should be managed to meet the edaphic requirements of rice and following dryland crops that use residual soil moisture. Turnaround times between successive rice crops and the following short-season dryland crop must be shortened to facilitate intensive land use. Tillage and water management play a vital role in intensifying land use.

PHYSICAL PROPERTIES OF RICE SOILS

Major rice soils include suborders Aqualfs, Aquults, Udults, Ustults, Aquents, Aquepts, Ochrepts, and Tropepts. Suborders of local importance are Udalfs, Ustalfs, Fluvents, Humults, Uderts, and Usterts. Some Aridisols are used for irrigated rice, for example, in Peru. The best soils for rice have high water retention capacity and low permeability.

Texture

Although rice grows on soils with a wide range of texture, fine-textured soils are the most suitable. Kawaguchi and Kyuma (17, 18) reported that 40% of rice soils in South and Southeast Asia contain at least 45% clay. Soils with coarse, loamy texture are planted to rice in Thailand and Sri Lanka. The coarse soils are sandy sediments with a clay subsoil. Loamy soils are in narrow inland valleys (24). Rice soils of West African floodplains are similar to those in Sri Lanka. In Surinam, rice soils are heavy-textured (30). Coarse-textured soils are generally less productive than clay soils.

Subsoil texture is as important as surface texture. The adverse effects of sandy surface horizons can be diminished if subsurface horizons are rich in clay. A profile with a medium-textured surface horizon and a clay subsoil is particularly good for rice. Provided they occur at depths greater than 50 cm, sandy subsoils generally cause no problems for rice production. Yahata (35) applied similar soil, water, and nutrient management to several Japanese rice soils of different texture (Table 1). He found that clays produced better rice yields than coarse-textured soils, except gravelly soil.

Mineralogy

Soils with a predominance of 2:l lattice clays are more productive than those with low-activity clays. De Datta et a1 (5) found that soils with high-activity clays yielded about 36% more than those with low-activity clays. Shoji (31) reported that most fertile Japanese rice soils have a high montmorillonite content. Kawaguchi and Kyuma (17, 18) had similar findings. Soil mineralogy influences rice production through its effect on soil physical properties and nutrient availability.

Structure

Traditionally, soil physical properties and structure have not been considered important for rice production. In fact,

Table 1. Soil texture and rice yield (35).

Soil[a]	Experiments (no.)	Grain yield (t/ha)	Relative (%)	Straw yield (t/ha)	Relative (%)
Muck soil	9	3.7	100	8.1	100
Clay	4	4.1		8.8	
Loam	5	3.3		7.5	
Strong gley soil	6	3.4	94	6.8	84
Gley soil	8	4.0	109	9.0	111
Clay	5	4.2		9.6	
Gley soil	8	3.7	100	8.8	108
Loam	3	3.5		8.4	
Grey brown soil	7	3.7	100	7.5	97
Loam	4	3.8		7.1	
Dark soil	3	3.7	100	7.9	98
Gravelly soil	8	4.4	119	9.6	110

[a] N = 1.2, P = 0.49, K = 1.15 kg/ha.

soil structure is deliberately destroyed by tillage for rice. These attitudes are changing in response to the need to increase land-use intensity and multiple cropping.

Recent studies in China and elsewhere show that fertile rice soils should have a good structure and a proper ratio between noncapillary and capillary porosity. Jia-fang and Shi-ye (12) showed that high-fertility rice soils have a ratio of air-filled porosity to total porosity of 0.22 at pF 2 as compared with 0.13 for low-fertility soils (Table 2). Adequate air-filled porosity facilitates leaching of toxic compounds, improves oxygen transport to roots, and increases N utilization and efficiency (12).

Less rigid soil structure and more total porosity and macroporosity are as important for lowland rice growth as for dryland crops. Research in India by Kar and associates (13, 14, 15) indicated that root penetration was greatest in soils with large total porosity and a high proportion of pores with radii exceeding 75 mm. Root growth was less with strong, compacted soil layers (Table 3). There also was interaction between bulk density and soil temperature. Soil temperatures exceeding 37° C adversely affected rice growth. Optimum porosity and pore size distribution vary among soils of different particle size distribution.

Permeability

Some percolation of water through rice soil is essential to regulate soil temperature, improve N-use efficiency, and leach away toxins produced by anaerobic decomposition of organic matter during rice growth (9, 35). Five to 20 mm percolation/d is necessary for high yield. Percolation exceeding 20 mm/d causes rapid leaching of nutrients. In China, Jia-fang and Shi-ye (12) reported higher N assimilation rates in permeable soils than in impermeable soils. Optimum permeability rate varies among soils and with different water management and fertilizer inputs.

Table 2. Soil porosity in the surface layer of high- and low-fertility rice soils (12).

Fertility	Porosity (%)		Air porosity ÷ total porosity
	Water-filled	Air-filled at pF 2	
Low	41.1 ± 2.1	6.4 ± 0.9	0.13 ± 0.02
High	40.2 ± 1.9	11.2 ± 2.8	0.22 ± 0.05

Table 3. Effect of bulk density and soil temperature on root growth of rice (16).

Bulk density (t/m^3)	Root dry mass (g)			Depth of root penetration (cm)		
	27/15°C	37/25°C	42/30°C	27/15°C	37/25°C	42/30°C
			Clay			
1.0	0.79	1.54	0.52	15.5	19.8	13.5
1.2	0.87	1.18	0.60	13.0	14.3	11.0
1.4	0.50	0.78	0.36	8.7	7.0	7.0
LSD (.05)		0.06			1.5	
			Loam			
1.4	0.59	1.07	0.41	13.5	16.7	11.5
1.6	0.74	0.67	0.46	9.8	9.2	9.0
1.8	0.44	0.40	0.31	6.0	5.7	5.3
LSD (.05)		0.08			1.1	
			Sandy loam			
1.6	0.62	1.44	0.45	14.3	23.5	13.3
1.8	0.72	0.87	0.56	10.7	12.8	9.5
2.0	0.37	0.50	0.28	5.5	5.2	4.5
LSD (.05)		0.07			1.0	

Soil depth

Deep rooting is important for rainfed rice during prolonged rainless periods and for dryland crops grown on residual soil moisture. Fertile soils promote deeper effective rooting than less fertile soils. With adequate water, however, deep rooting is unnecessary for high rice yields. Adequate rooting depth also varies with soil texture -- 10–14cm for a clay soil, 14–16 cm for loam, and more than 16 cm for a sandy soil (35). Rice yield also is influenced by the interaction of rooting depth, surface soil compaction, and subsoil properties. Jia-fang and Shi-ye (12) found that rice root mass increased linearly with depth of the surface soil.

TILLAGE FOR RICE

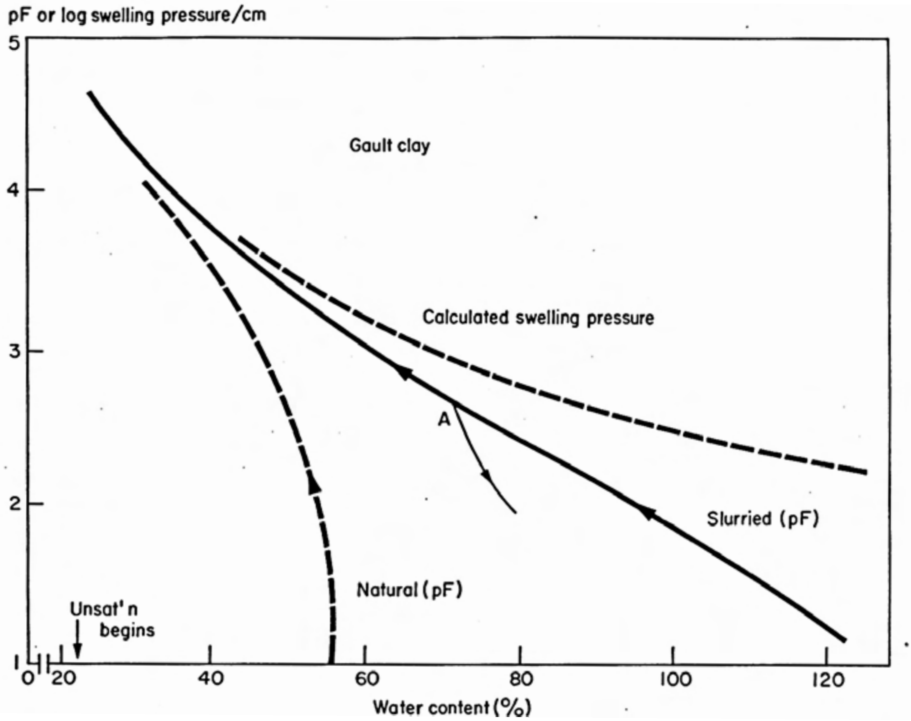
Usually, both dry and wet tillage are necessary to prepare soil for rice. Tillage changes soil porosity and pore-size distribution and hence permeability and percolation, and water retention capacity of the surface layer. The type, method, and frequency of tillage vary with soil texture, mineralogy, and antecedent soil physical properties.

Puddling

Puddling changes soil into a homogenous suspension of primary particles. Puddling is easiest when soil is near field moisture capacity or the lento-capillary point. Puddling destroys aggregates, increases porosity, moisture retention, and reducing conditions, and lessens bulk density and permeability. The process is more thorough in soils with 2:1 clays than in coarse-textured soils with low-activity clays. Swell-shrink characteristics are important in puddling, and some soils therefore puddle more effectively than others. The first step in puddling is to decrease cohesion among soil units by regulating moisture content.

Puddling a clay soil increases pore volume, at least temporarily, but the volume of interaggregate or transmission pores substantially diminishes. In contrast, the volume of storage pores increases (2, 34) (Fig. 1).

Effective puddling drastically reduces a soil's permeability as compared to its aggregated state. Sanchez (29) recorded a large decrease in drainage rates of puddled Philippine rice soils. Puddling decreased percolation losses



1. Comparison of soil-water retention characteristics of structured and slurried clay soils (34). Unsat'n = unsaturation.

Table 4. Effect of puddling on drainage rates of 6 Philippine rice soils (29).

Soil		Clay (96)	Drainage (cm/d)	
			Aggregated soil	Puddled soil
Psamment	Siliceous	9	267	0.45
Fluvent	Mixed	24	215	0.17
Aquept	Montmorillonitic	30	183	0.05
Aqualf	Montmorillonitic	40	268	0.05
Ustox	Kaolinitic	64	155	0.05
Andept	Allophanic	46	214	0.31
Mean			217	0.18

by a factor of 1,000 regardless of soil properties (Table 4). If a soil has been puddled for many years, a low permeability 5- to 10-cm-thick plow pan that reduces permeability probably has developed immediately beneath the puddled layer (12). Yun-Sheng (37) found that although bulk density and total porosity of the plow pan were not drastically different from those of the cultivated layer, hydraulic conductivity often was considerably less (Table 5). Hydraulic conductivity of the plow pan is lower because the transmission pores have been changed to capillary pores. De Datta and Kerim (6) found that puddling reduced percolation and therefore reduced water consumption.

Wet tillage effects on soil physical properties are greatest for easily puddled soils, for example, fine-textured soils, with high activity clays, that are aggregated when dry. Puddling has little or no effect on coarse-textured soils, or on soils that are easily dispersed, such as fine-textured soils with high exchangeable sodium percentage (ESP), or sodic soils. To save time and expensive

Table 5. Comparison of soil physical properties of the cultivated layer and of the plow pan of a rice soil in tne Taihu Lake region of China (37).

Soil property	Cultivated	Plow pan
Bulk density (t/m^3)	1.20 ± 0.07	1.35 ± 0.09
Total porosity (%)	53.5 ± 2.6	50.0 ± 3.4
Pores > 0.2 mm diam (%)	11.5 ± 3.1	5.4 ± 2.3
Pores 0.2-0.01 mm diam (%)	4.6	2.6
Pores < 0.005 mm diam (%)	35 ± 3	41 ± 3
Hydraulic conductivity (cm/d)	1040	1.7

inputs, it is important to identify soils that can be manipulated by wet tillage from those that cannot or should not.

Long-term effects of puddling

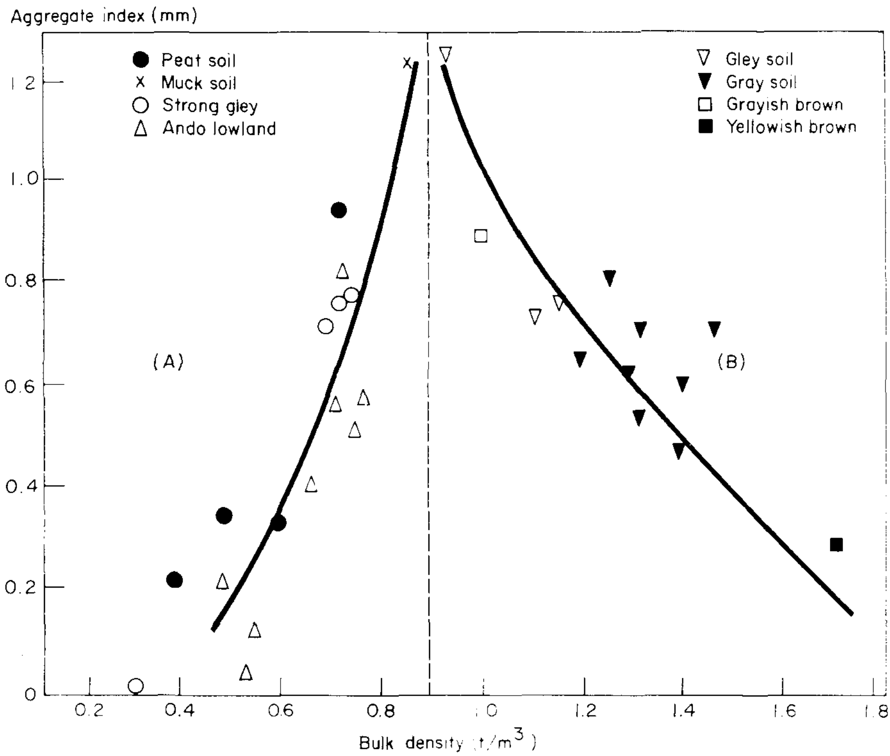
Soils that are repeatedly puddled over many years undergo drastic structural changes. These changes differ with soil texture and mineralogy. When puddled soils dry, they shrink and develop weak structures with smaller proportions of water-stable aggregates. Terasawa (33) described physical properties of some Japanese rice soils and observed that the plow pan is invariably harder than the surface layer. He also found that aggregation index increased with bulk density in organic soils but decreased in inorganic soils (Fig. 2). When a puddled soil dries, water retention capacity decreases more than for an aggregated soil. During prolonged rainless periods under rainfed conditions, a rice crop in puddled soil may therefore experience more drought stress than in an aggregated soil.

Rice response to puddling

Effects of puddling on crop growth are hard to generalize. They vary among soils and are influenced by soil and crop management. Puddling generally benefits rice growth in soils where wet tillage causes radical changes in physical properties. In other soils, rice yield is hardly affected.

<u>Well-structured clay soils</u>. Destroying the structure of a well-aggregated clay soil or of a soil with a high proportion of water-stable aggregates often increases rice yield in comparison to yields when such soils remain aggregated. Puddling thus improves yields in soils with structural or interaggregate transmission pores that cause high permeability (Table 4). Table 6 shows how lowering percolation on a well-structured soil in tanks increased rice yield.

Mabbayad and Buencosa (21) compared rice grain yields on Maahas clay with conventional puddling and with zero and minimum tillage and with different rates of paraquat for weed control. They found that rice yielded well on unpuddled soil with adequate chemical weed control (Table 7). For rainfed rice, De Datta and Kerim (6) concluded that puddling does not significantly increase yield on clay soils. The following upland crop, however, may benefit from the structure of unpuddled soil.



2. Relationship between aggregate index and soil bulk density for inorganic and organic soils (33).

Table 6. Effect of puddling Maahas clay on rice yield and N use efficiency (6).[a]

Pianting method	Tillage method	Grain yield (t/ha)	Plant N content (%) at flowering
	No N		
Transplanted	Puddled	3.0 de	0.9 b
Broadcast	Puddled	3.5 bcd	0.8 b
Row-seeded	Nonpuddled	2.2 f	0.9 b
	75 kg N/ha		
Transplanted	Puddled	4.0 abc	1.2 a
Broadcast	Puddled	4.1 ab	1.3 a
Row-seeded	Nonpuddled	2.8 ef	1.1 ab
Transplanted [b]	Puddled	4.6 a	1.2 a
Row-seeded [b]	Nonpuddled	3.4 cd	1.2 a

[a] Separation of means in a column by Duncan's multiple range test at the 5% level: [b]Flood-irrigated to 5-cm depth.

Table 7. Effect of tillage method on lowland rice yield on Maahas clay (21).

Tillage method	Grain yield (t/ha)	
	Wet season	Dry season
	1966	
Plowed and harrowed	3.3	6.4
No-till (0.4 kg paraquat/ha)	2.0	6.7
No-till (0.8 kg paraquat/ha)	2.9	6.9
Plowed and rototilled	2.9	6.4
Plowed only	2.0	7.2
LSD (.05)	ns	ns
	1967	
Plowed and harrowed	3.0	4.9
Rototilled (0.4 kg paraquat/ha)	3.0	4.6
Rototilled (0.6 kg paraquat/ha)	2.7	4.4
Rototilled (0.5 kg PCP oil/ha)	2.6	4.5
No-till (0.6 kg paraquat/ha)	2.9	-
LSD (.05)	ns	ns

Easily dispersed clay soils. Soils that are easily dispersed on wetting do not need tillage to destroy their structure. They are self–puddling and have little deep per–colation and slight or no leaching. Wet tillage does not alter their physical properties, and therefore has little effect on rice growth and yield. Vertisols, especially those with high ESP, are such soils. Because these soils are self–mulching, they also do not need dry tillage. Croon (3) stud–ied the effects of three tillage methods on rice grown on a Vertisol in Kenya, His data (Table 8) show no significant yield reduction in unpuddled plots, nor was bulk density affected by tillage method. Tractor bogging in flooded fields was a major hazard in these soils.

Floodplain soils of mixed mineralogy. Floodplain soils are poorly drained and have low permeability. Unless drain–age is improved, toxins accumulate and adversely affect rice growth and yield. The heavy, fluvio–marine clay soils of the Central Surinam Plains are an example. They contain 65% clay (32), and that clay fraction comprises 40% kaolinite, 20% montmorillonite and chlorite, 20% illite, and 20% quartz. Their structure and permeability can only be improved by dry tillage followed by thorough drying. Puddling did not im–prove yield over that with dry tillage (Table 9). Wet or dry tillage did not affect permeability at 45-100 cm depth.

Table 8. Effect of tillage methods on rice yield on a Vertisol (Aeric Grumaquartz) in Kenya (3).

Season	Tillage method	Grain yield (t/ha)	Productive tillers/hill	Soil bulk density (t/m³)
1975 Long rains -	Zero tillage	4.9	12	1.03
	Paraquat	5.1	12	1.01
	Standard tillage	5.4	10	1.02
1975 Short rains	Zero tillage	3.2	18	-
	Paraquat	3.4	18	-
	Standard tillage	3.4	19	-

Surface permeability for both tillage treatments was below optimum for rice (Table 10). In these soils, dry tillage is more suitable than wet tillage or puddling.

Coarse – textured soils with low – activity clays. Poorly structured soils or those with single – grain loose structure are highly permeable. When flooded, leaching of applied fertilizer is high. Plowing, harrowing, or rototilling often have little effect on physical properties or consequently on yield. Examples are the valley bottom, coarse – textured soils used for rice cultivation in West Africa and Sri Lanka.

An international coordinated project of the University of Wageningen, Netherlands, evaluated the effect of tillage method on lowland rice yield in Senegal, Nigeria, and India. Neither the intensity nor type of wet or dry tillage over 2 – 3 yr significantly affected rice yield in

Table 9. Effect of tillage method on rice yield in Surinam at different fertilizer rates (30).

Tillage	Mean yield (t/ha)
56 kg N/ha	
Wet	3.3
Dry/wet	3.5
Dry	3.4
Zero	3.2
84 kg N/ha	
Wet	3.9
Dry/wet	3.8
Dry	3.8
Zero	3.4

Table 10. Effect of tillage method on physical properties of a clay floodplain soil in Surinam and on rice grain yield (30).

Soil property	Wet tillage	Dry/wet tillage	Dry tillage	Zero tillage
Available moisture (%)				
up to pF 2.7	28	19	21	15
pF 2.7-4.2	40	34	30	30
Range of water permeability (15-45 cm depth) (mm/d)	0-3	4-15	8-70	
Range of dispersion ratio[a] (%)	31-78 (43)	52-72 (56)	16-48 (37)	33-45 (32)
Water stable aggregates[a] (%)	64-72 (69)	67-75 (70)	71-74 (73)	70-76 (74)
Rice grain yield (t/ha)				
at 56 kg N/ha	3.7	3.5	3.4	3.2
at 84 kg N/ha	3.9	3.8	3.8	3.4

[a] Figures in parentheses are mean values.

Senegal (Table 11). In Nigeria, tillage on a sandy soil also had little effect on rice grain yield (Table 12). On a clay-loam soil in India, however, disc harrowing produced somewhat higher yields than plowing (Table 13). Lack of rice yield response to wet or dry tillage also was reported for Sri Lankan soils (23).

The effect of no-till and puddling on rice yield from sandy loam and sandy-clay loam soils was studied for 15 consecutive crops at IITA, Ibadan, Nigeria. Maurya and La1 (22) and Rodriguez and La1 (28) found that both tillage methods gave similar yield if weeds were controlled.

Figure 3 shows-effects of no-till and puddling on grain yield for seven consecutive rice crops on a sandy loam soil. The low yields for crops 4-6 in the no-till treatment were because of poor seedling establishment. Rice straw was always left on the surface, and anaerobic straw decomposition

Table 11. Effect of wet and dry soil tillage by a 2-wheel tractor-mounted rototiller on grain yield and weed mass density in Senegal (7).

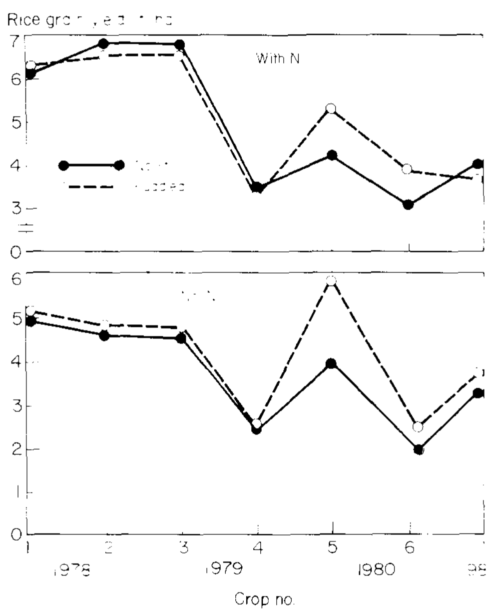
Tillage method	Main season 1974		Off-season 1974	
	Yield (t/ha)	Weed mass density ($kg/20m^2$)	Yield (t/ha)	Weed mass density ($kg/20m^2$)
Dry	2.5	4.7	2.4	14.0
Wet (1 pass)	2.3	3.8	2.1	8.5
Wet (2 passes)	2.5	2.8	2.5	7.0
Wet (5 passes)	–	–	2.5	8.5
Significance	ns	ns	ns	0.5%

Table 12. Effect of wet and dry tillage on yield of IR20 on sandy soil at International Institute of Tropical Agriculture, Nigeria (7).

Tillage method	Rice grain yield (t/ha)	
	With fertilizer	Without fertilizer
No-tillage	5.5	5.4
Rotary tillage (1 pass)	5.7	4.8
Rotary tillage (4 passes)	5.9	5.4
Japanese reversible plow	6.0	4.3
Mean	5.8	5.0
LSD (.05)		
Fertilizer	1.4	
Tillage	ns	

Table 13. Effect of bullock-drawn tillage on rice yield on a clay loam soil at Cuttack, India (7).

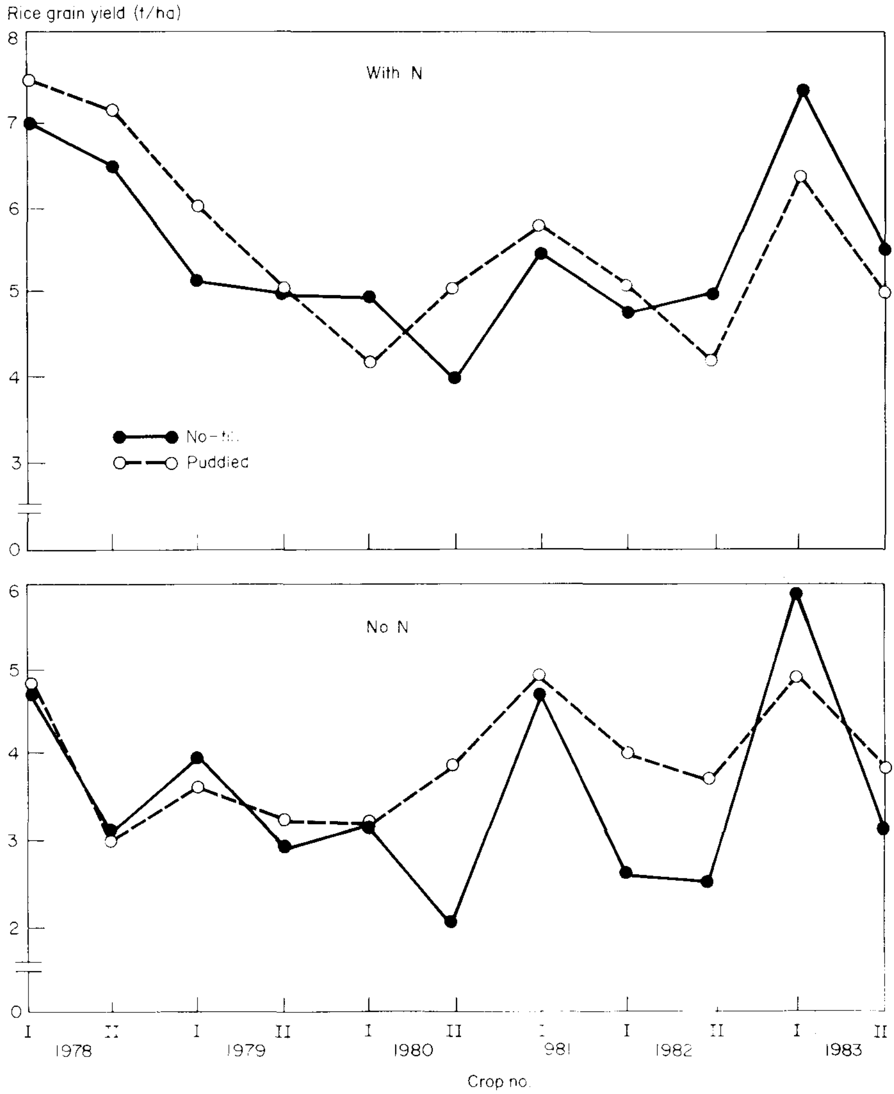
Wet tillage	Grain yield (t/ha)	
	With dry primary tillage	No primary tillage
Plowing	3.9	3.5
Disc harrowing	4.3	4.0



3. Rice grain yield on puddled and no-till sandy loam soil with and without nitrogenous fertilizer.

produced toxic compounds that may have reduced seedling establishment. Seedling establishment and rice yields improved when crop residues were removed. Similar results were obtained on a sandy-clay loam soil (Fig. 4). Crop residue reduced yield less on the heavy-textured soil.

IITA data indicate that tillage method affects soil physical properties only slightly. The surface 0-1cm layer



4. Rice grain yield on puddled and no-till sandy-clay loam soil with and without nitrogenous fertilizer.

Table 14. Effect of tillage method on textural proportions of a coarse-textured soil in western Nigeria (Lal, 1981, unpubl. data).

Soil constituent	Textural proportion (%)					
	Puddled			No-till		
	0-1 cm	1-2 cm	2-5cm	0-1 cm	1-2 cm	2-5 cm
Sand	32	30	31	28	28	30
Silt	33	33	32	34	34	33
Clay	35	37	37	38	38	37

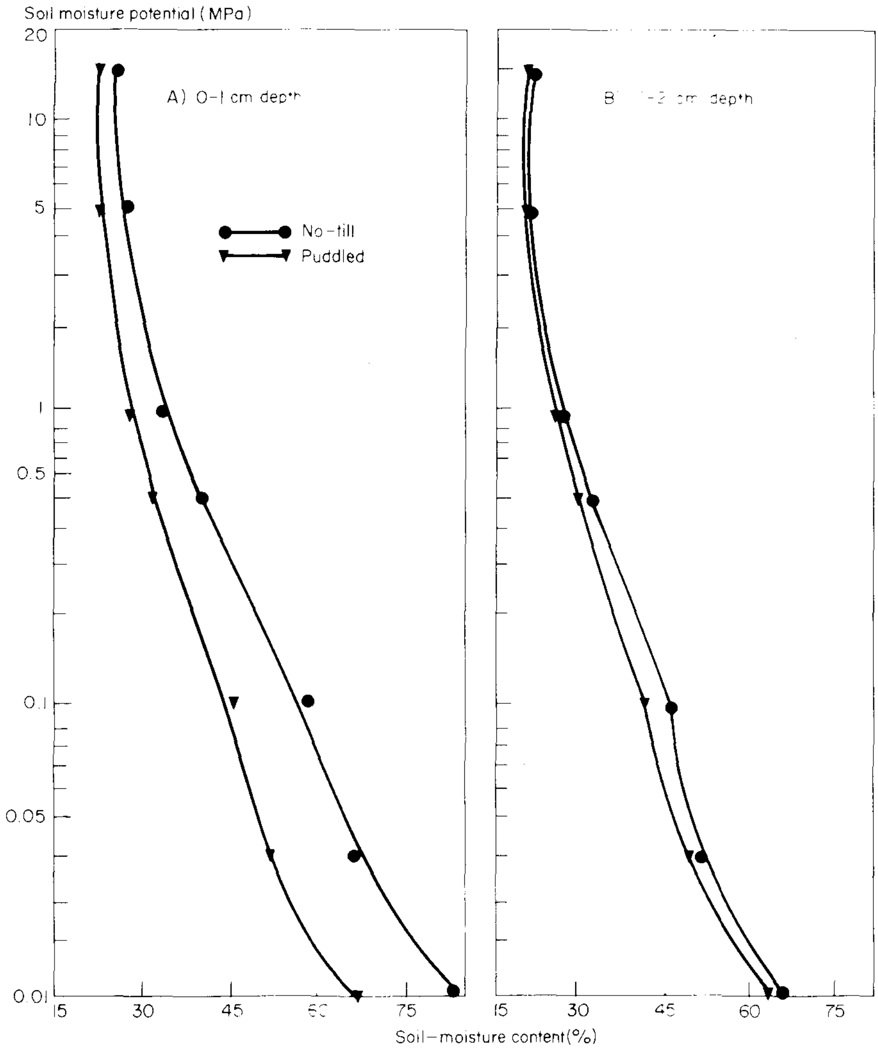
of puddled plots had less clay and silt and more sand than the no–tillplots (Table 14). The surface layer of no–till plots retained more water at all suctions than on the pud–dled plots (Fig. 5). These effects were pronounced only in the 0–1cm layer. Bulk density in no–tillplots was low in the surface horizon and increased between 2 and 6 cm. In contrast, the high bulk density of puddled soil at 0–1cm decreased between 1 and 4 cm and increased between 4 and 8 cm (Fig. 6).

These data and those by Curfs (4) indicate somewhat different features of rice profile development in coarse–textured and clay soils. Curfs observed that the plowed/–puddled layer in a sandy soil can be divided into four sub–layers. The 0.5–2.0mm top layer usually consists of clay and silt. The 5–20mm sublayer is mostly sand. The second sublayer extends to plow depth (12–13cm). The third sub–layer corresponds with a plow pan but is poorly developed.

Mechanical compaction of coarse–textured soils and effect on rice yield

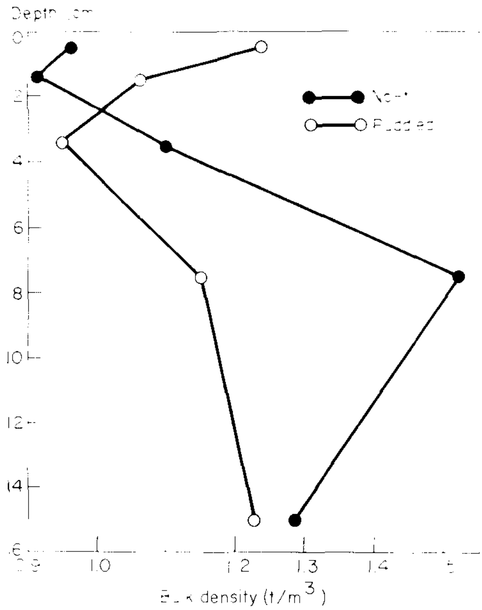
Although puddling does not reduce percolation in coarse–textured soils, compaction can. Ghildyal (8) reported that a soil at 1.7 t/m^3 bulk density had substantially lower cumu–lative water intake than a soil with 1.5 t/m^3 bulk density. Increased rice grain yield on a compacted soil, especially in a pot experiment, is difficult to interpret because of the differences in total soil weight. Some increase in field grain yield has been observed where water availability was not limiting.

In Nigeria, Ogunremi et a1 (25) compared alterations in soil physical properties and rice grain yield from a sandy



5. Soil moisture retention properties of a no-till and a puddled sandy loam soil during the off-season.

loam soil following puddling, no–till,and compaction. Their data (Table 15) show that rice yield from the compacted soil was highest. Compaction probably decreased leaching of applied fertilizer (Table 16). In rainfed rice, however, rice grown on compacted soil is likely to have severe drought stress during rainless periods because compaction may decrease water storage capacity in some soils.



6. Bulk density profiles in a no-till and a puddled sandy loam soil during the off-season.

Table 15. Effect of soil compaction on rice yield on a sandy loam soil in western Nigeria (26).

Tillage method	Grain yield[a] (t/ha)			Bulk density (t/m^3)	Void ratio	Transmission pores > 50 µm (%, vol/vol)	Air-filled porosity at 0.1 bar suction (%)
	I	II	III				
Compacted	7.9	4.1	7.6	1.68	0.95	7.4	9.2
Puddled	6.6	3.5	5.1	1.50	0.97	7.9	9.5
No-till	5.9	3.3	5.6	1.46	1.04	8.2	10.1
LSD (.05)	1.1	0.5	1.9	0.10	0.04	0.3	0.4

[a] I, II, III are consecutive rice crops.

Table 16. Effect of tillage method on cumulative water infiltration of a sandy loam soil (26).

Tillage method	Cumulative water infiltration (mm)			
	10 min	50 min	90 min	120 min
Compacted	25	42	47	55
Puddled	29	48	57	57
No-till	34	61	73	87

Effects of puddled soil on following dry season crops

Use of lowland rice fields for post-rainy season dryland crops is increasing. Growth and yield of the dryland crops are influenced by soil mechanical properties, soil temperature, and moisture regimes after rice. Low soil bulk density and favorable pore size distribution are necessary for roots to penetrate the subsoil and use residual moisture. Dryland crops grow badly on poorly structured, puddled soils. Soil physical constraints created by puddling can be alleviated by appropriate tillage, but the necessary operations require high energy inputs, are capital intensive, and often are impossible for small landholdings in the tropics.

An untilled, puddled soil adversely affects root penetration of upland crops. For example, Hundal and De Datta (10) found that while mungbean yield was unaffected by dry season tillage, sorghum yield was higher in tilled than in untilled plots. Dry season tillage improved sorghum water-use efficiency, for example, 0.56 kg/m^2 of dry matter production with 17 cm of water for a tilled seedbed compared with 0.33 kg/m^2 of dry matter with 22 cm of water for an untilled seedbed. This was attributed to different nutrient availability under the two tillage methods.

Dry season soil management also influences establishment and yield of the following rainy-season rice crop. Dry, hard soil requires considerable time and energy to prepare a seedbed for timely establishment of rice. A weed-free seedbed protected from ultra-desiccation by a crop residue mulch benefits the following rice crop (11).

Rice seedling emergence and establishment under anaerobic conditions

Rice seedling establishment often is adversely affected by organic chemicals released during anaerobic decomposition of crop residues. The effects are particularly severe in untilled fields with coarse-textured soil. Low toxin concentration in sandy soils produces the same effect as high concentration in clay soils. The problem can be partially overcome by dry tillage, wet tillage, or by burning or removing crop residue. Tillage often is expensive and adversely affects the following dryland crops.

Oxygenating compounds have produced encouraging results in alleviating the adverse effects of anaerobic conditions.

Table 17. Effect of calcium peroxide application on seedling emergence and yield of IR36 (36).

Sowing method	Calcium peroxide coating	Emerged seedlings (no./m^2)	Grain yield (t/ha)
Machine seeded	With	174	5.5
	Without	8	0.6
Broadsast, flooded	With	216	5.4
	Without	30	2.7
Broadcast, drained	Without	259	5.6
Transplanted		25	5.4

Experiments at IRRI by Yoshida and Parao (36) showed that rice seedling establishment under anaerobic conditions can be improved by applying calcium peroxide (Table 17). Japanese studies showed that peroxide seed coating improved germination under submerged conditions (27).

The adverse effects of puddling and structural deterioration on off-season dryland crops also can be minimized by applying oxygenating compounds. Dryland crops, such as cowpea, grown on poorly drained soils often suffer from anaerobic conditions. Tillage can oxygenate the soil, but often is expensive and self-negating. Ogunremi et a1 (25) found that calcium peroxide application improved crop emergence, leaf area, dry matter, and grain yield of cowpea grown in a poorly drained soil (Table 18).

Table 18. Percent emergence and grain yield of cowpea and soybean as affected by water table depth and calcium peroxide application (25).

Water table depth (cm)	Calcium peroxide application	Emergence (%)		Grain yield (g/plant)	
		Cowpea	Soybean	Cowpea	Soybean
0 (saturated)	Without	44	8	0.1	0.0
0 (saturated)	With	72	19	1.4	0.7
15	Without	83	44	18.9	2.9
15	With	92	36	24.3	5.4
40	Without	48	25	26.5	4.5
40	With	81	19	27.8	5.6
LSD (.05)					
Water table		15	19	4.2	2.3
Calcium peroxide		12	16	3.4	1.9

Trafficability of rice soils

Heavy clay soils are very hard when dry and very sticky when wet. Their trafficability, workability, and soil–implement interaction are not well understood. The scanty available information indicates that puddling decreases the range of soil moisture content for efficient workability. Tractors and buffalo often bog down in a clay soil that is plowed at field moisture capacity or near saturation. This frequently occurs in old rice fields. Soil workability progressively deteriorates, making it necessary to drain and dry the fields.

Plowing a dry, puddled soil is equally difficult because the hard, structureless soil has undergone considerable shrinkage, Plowing a hard–setsoil that has broken into large, massive clods often is beyond the capacity of animal power, which commonly is the only power available in South and Southeast Asia. These difficulties in wet and dry plowing of heavy clays are caused by tillage–inducedalterations in soil structure. Unnecessary or excessive tillage of clay soils also causes trafficability problems.

Kisu (19) related machine performance during wet tillage with soil properties. Traction performance or traction ratio (drawbar pull divided by tractor weight) is related to soil resistance. With progressive soil structure deterioration caused by successive puddling, the tractor sinks deeper and deeper into the soil. Sinkage depends on tractor weight per unit area and soil strength (30). Kisu (19) developed a tentative rating index to assess the ease of different tillage operations in a wet soil in relation to cone index (Table19).

SOIL PROPERTIES AND TILLAGE FOR RICE–BASED CROPPING SYSTEMS

The need for more food has necessitated agricultural diversification on the rice soils of South and Southeast Asia. The dryland crops usually grown on rice soils in double–or multiple–croppingsystems are vegetables and pulses such as mungbean, cotton, tobacco, peanut, and mustard (18). Tillage of heavy–texturedsoils for dryland crops must facilitate seedling emergence and increase water–holding capacity. Dryland crop emergence is poor on puddled soils, and crops suffer from drought. On sandy fan terraces, soil structure and water–holdingcapacity are poor.

Appropriate tillage matches requirements for growing rice and the following dryland crop with the soil proper–

Table 19. Relation between cone index and trafficability of a wet soil for different tillage operations (19).

Tillage operation	Cone index (MPa) at given trafficability		
	Easy	Possible	Impossible
Rotary tilling	> 0.5	0.3-0.5	< 0.3
Plowing	> 0.7	0.4-0.7	< 0.4
Plowing (with griddle)	> 0.4	0.2-0.4	< 0.2

ties. A desirable rice soil should have low permeability, 10 to 20 mm/d, and high water retention capacity in the surface layer. Additionally, soil management must ensure adequate crop stand by improving seedling emergence in direct sown rice, and facilitate rice transplanting. Soil structure also must ensure an economic yield froma following dryland crop.

Tillage type and intensity depend on the antecedent soil physical conditions. Apparently controversial results reported in the literature regarding the effects of puddling on rice growth can be explained in terms of soil properties. It is difficult to generalize tillage recommendations for rice without regard to soil conditions. Land–usehistory is equally important to this evaluation. Thus:

- On soils with predominantly high–activityclays, on soils that are easily dispersed when submerged, and on soils with naturally low permeability, with adequate weed control, rice grows successfully without puddling. If puddling is at all necessary, it can be done every 3 or 4 yr rather than for every crop. Under these conditions, eliminating puddling would improve growth and yield of following dryland crops, as would mulching.
- In unpuddled coarse–texturedfields with predominantly low activity clays, yield is reduced because of high percolation and nutrient leaching, and because of nutrient imbalance and toxicities. Crop residues should either be removed or burned. Soil permeability should be reduced. Because effective puddling is impossible in poorly structured soils, they respond better to soil compaction than to wet or dry plowing. Dry tillage may be necessary if a dryland crop is grown after rice.
- Compacted soils with poorly drained subsoil and surface horizons of low air–filledporosity respond more to dry than to wet tillage.

- On well-structured clay soils with high percolation, puddling is necessary. The frequency and intensity of puddling may be lessened when a low-permeability plow pan develops. Dry tillage may be required if structural conditions do not improve enough for a dryland crop in dry season. However, using oxygenating compounds may be a promising technique for improving crop stand and growth.

It is important to develop scientific criteria for choosing appropriate tillage systems. Considerable basic and applied research is needed to develop such guidelines. Important considerations in developing the criteria will be clay content and mineralogy; permeability, compaction, and internal drainage; trafficability; days available for seedbed preparation; and crop rotation. La1 (20) developed a tentative system for assessing soil tillage requirements for a rice-based system (Table 20). It can be improved by adding independent variables such as soil compaction and soil strength. Rice grown on soils with low tillage rating is likely to respond to compaction. Soils with ratings of 2-3 may require varying intensity of puddling, depending upon land use history and the presence of a slowly permeable plow pan. Wet tillage should be avoided on soils with ratings of 4-5. Some soils with high ratings may require periodic dry tillage to increase air-filled porosity.

CONCLUSIONS

Puddling decreases permeability, increases water retention capacity, facilitates transplanting, and eradicates weeds. Heavy-textured soils with high-activity clays puddle more effectively than coarse-textured soils. Puddling may benefit

Table 20. Tentative rating table as a guide to tillage requirements for rice-based cropping systems (20). Rating is cumulative.

Clay content (%)	Cation exchange capacity (mmol/kg)	Soil permeability (mm/s)	Endurance to traffic for wet tillage	Days available for seedbed preparation	Rating
< 10	< 50	> 70	Very good	<15	1
10-25	50-100	35-70	Good	15-25	2
25-40	100-150	17-35	Fair	25-35	3
40-55	150-200	1-17	Poor	35-45	4
>55	> 200	<1	Very poor	>45	5

rice growth in soils with high percolation rates. Dryland crops grown on puddled soils may, however, suffer from poor soil structure and drought stress because of soil shrinkage and root growth impedance below the plow pan. Puddling does not benefit rice growth and yield on naturally dispersed soils, such as Vertisols. Poorly drained soils, however, respond better to dry than to wet tillage. Percolation rates of coarse-textured soils may be more effectively decreased by mechanical compaction than by wet tillage.

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IMPLEMENT DESIGN FOR LOWLAND RICE-BASED CROPPING SYSTEMS

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Abstract

This paper examines the basic tillage implement requirements of a lowland rice-basedcropping system. Basic cultivation operations and the types of soil disturbance needed for each are identified. Soil and implement factors influencing draft and power requirements are considered, and the action and type of soil disturbance caused by the different implement types is described. A method of choosing the basic implement types necessary for specific field situations is suggested, and appropriate tools and techniques are recommended.

IMPLEMENT DESIGN FOR LOWLAND RICE-BASED CROPPING SYSTEMS

Precise knowledge of necessary soil conditions and of the transformations needed to achieve them is a prerequisite for efficient equipment design and selection for any cropping system. For implement design, it is convenient to define the required soil manipulations based on cultivation operations needed to change the existing to the desired soil state (4). Several basic cultivation operations can be identified for lowland rice-based cropping systems.

After basic cultivation operations are identified, implements can be designed and perfected (2). Implements must produce desired results under prevailing soil and moisture conditions, require minimum power and draft, and match available power units and farm and field size and shape.

BASIC CULTIVATION

At the beginning of the rice phase in a lowland rice-based cropping system, the soil often is compacted and covered with weeds or trash. Tillage must loosen the soil and control weeds through incorporation by mixing or inversion. Loosening is followed by puddling to move the organic material deeper and reduce soil permeability at the bottom of the puddled layer.

Permeability can be reduced by mechanical soil manipulation and by forcing soil particles down to decrease pore size at the bottom of the puddled layer. Leveling may be needed before transplanting. Where upland crops will be planted after rice, soil loosening, clod breaking, and soil compaction may be necessary.

NATURE OF SOIL DISTURBANCE

During tillage, forces applied by the implement make clods or aggregates slide over each other into new positions. Three types of disturbance occur, depending on soil condition and implement type and force (3).

- Loosening or brittle disturbance. Soil slides along a few well-defined planes and soil density declines.
- Compacting or compressive disturbance. Particles move along many planes and soil density increases.
- Critical state disturbance. Particle movement does not change soil density.

Table 1. Type of soil disturbance for basic cultivation operations.

Operation	Required disturbance
Loosening	Brittle
Mixing	Any [a]
Inversion	Any [a]
Compaction	Compressive
Leveling	Any [a]
Clod disintegration	Brittle

[a] Type depends upon the required change in density.

The success of any tillage operation depends on moving the soil in the right way. Table 1 shows the necessary movements for basic cultivation operations.

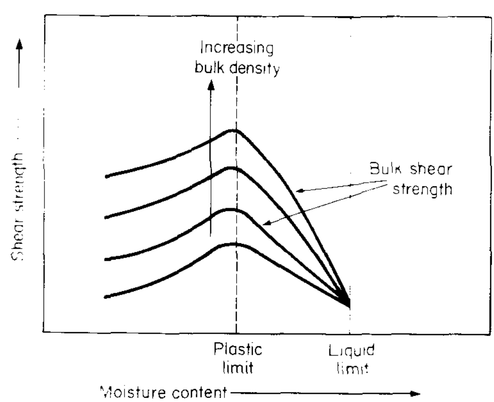
Loosening often becomes more difficult as soil becomes wetter or looser. Compression is less likely at higher compaction and at saturation.

Implement shape determines soil movement, and the type of soil disturbance. Loosening occurs when soil is moved toward the surface or to a cavity where it can expand. Implements move soil along the path of least resistance. Moving soil into soil causes compression.

SOIL RESISTANCE TO DEFORMATION

Moisture content and packing state substantially influence soil resistance to deformation. Figure 1 shows how moisture content and soil density affect bulk shear strength in a large mass of well-structured or medium- to coarse-textured soil. Shear strength increases with drying and density.

1. Soil bulk shear strength - moisture content relation.



Drying also rapidly increases deformation resistance (clod shear strength) of individual clods or aggregates (Fig. 2). Clods are most easily broken at high moisture content, which is the ideal state for puddling, but the most vulnerable state for soil-structure deterioration in the non-rice phase of the cropping sequence. In this non-rice phase, it is best to break clods when the soil is friable and drier than the plastic limit.

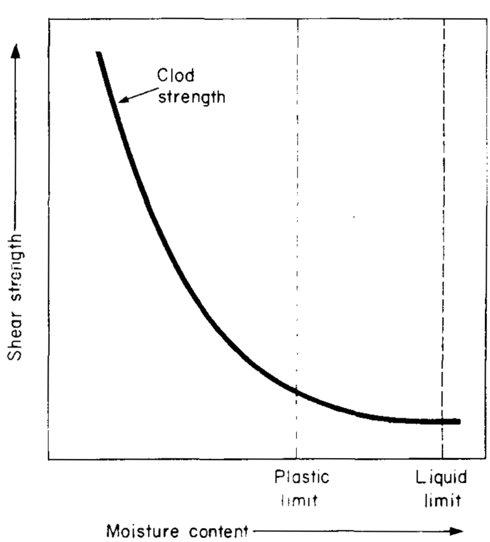
Bulk and clod shear strengths in poorly structured, fine-textured soils react similarly to drying: both become exceptionally high at low soil-moisture content.

The sliding resistance of a soil over implements is greatest near the liquid limit, where scouring may be impossible in finer textured soils.

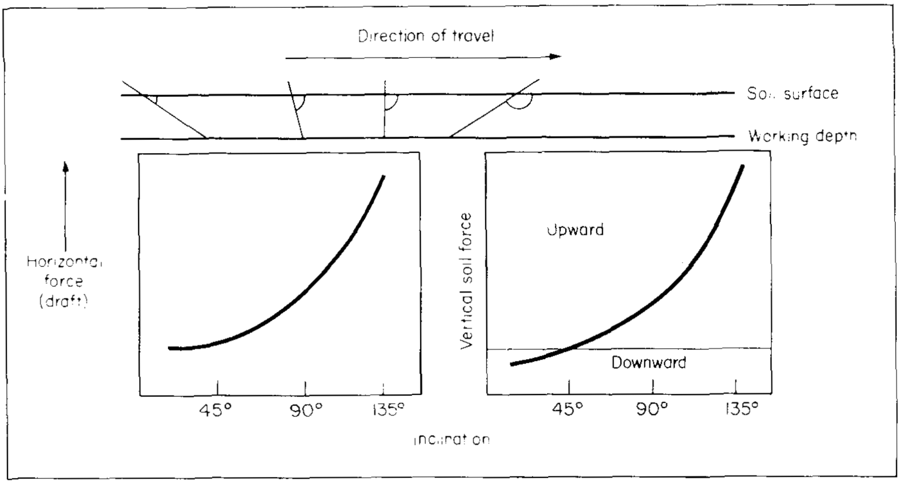
IMPLEMENT FORCES AND POWER REQUIREMENTS

Implement forces and power requirements relate directly to soil condition, deformation resistance, and implement geometry and working depth. Figure 3 shows the sensitivity of horizontal and vertical forces acting on tines or blades to changes in horizontal implement inclination at the same working depth.

Draft (horizontal) forces can be minimized by using the smallest possible tine inclination for the appropriate soil



2. Clod shear strength - moisture content relation.

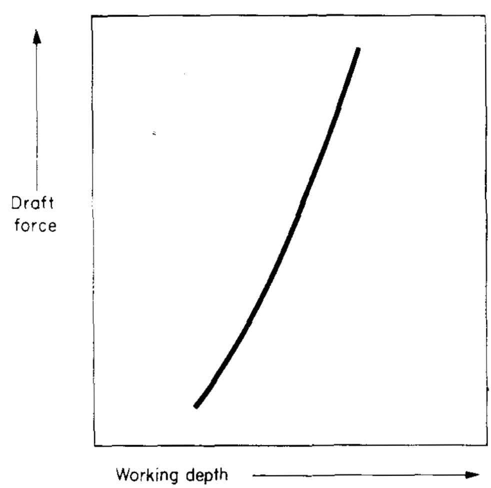


3. Influence of tine inclination on soil forces. Draft force is lowest and penetration highest at low inclinations.

disturbance. Tines with low inclination should be selected for soils with penetration problems. Large inclinations are needed when penetration is unnecessary or when heavy downward loads are required to break clods or to smear or to puddle the soil.

Tillage depth should always be minimized because of draft and power penalties for deeper cultivation (Fig. 4).

4. Influence of tine working depth on draft force.



IMPLEMENT ACTION ON SOIL

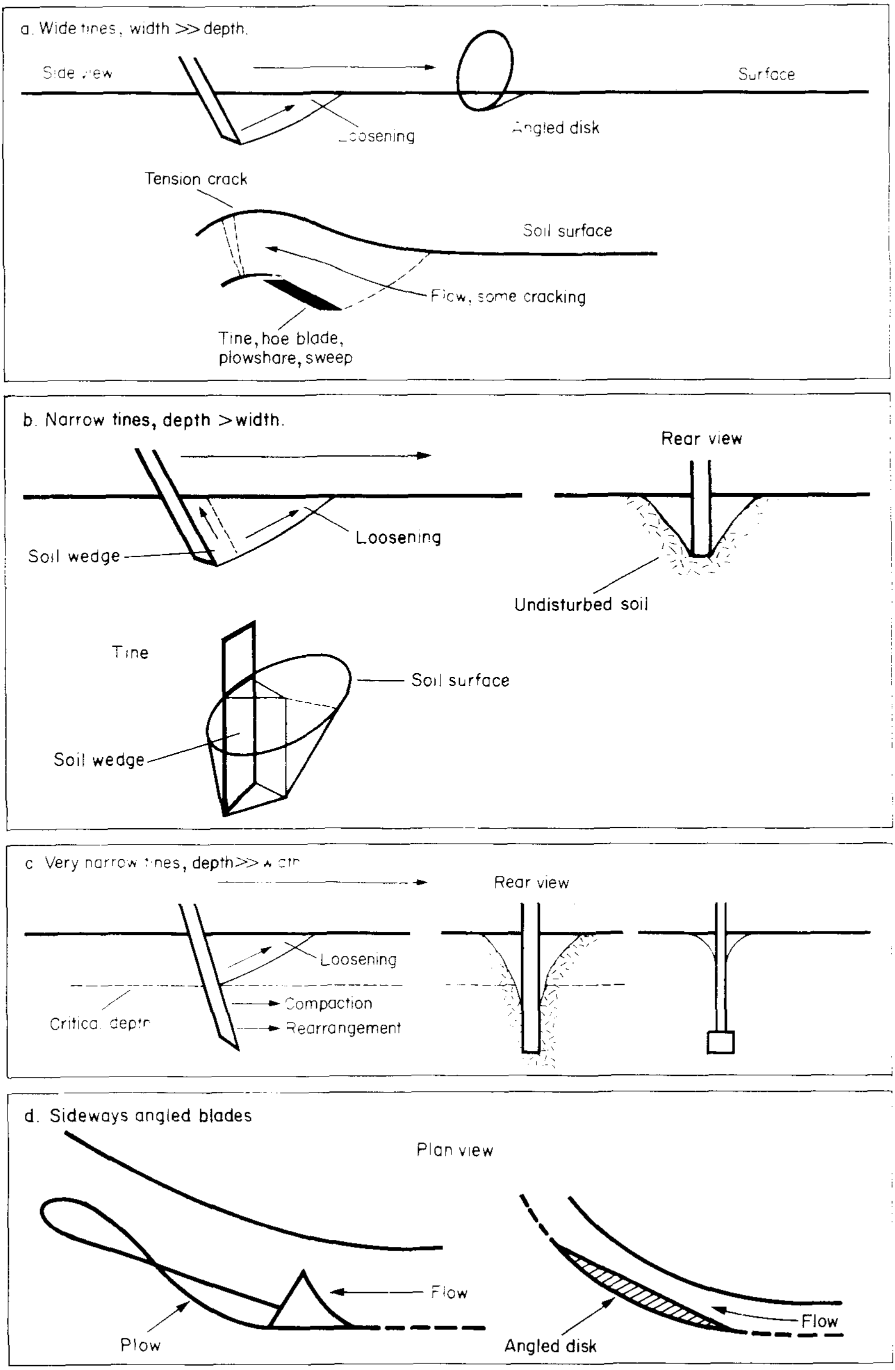
Implements can be grouped according to patterns of soil disturbance.

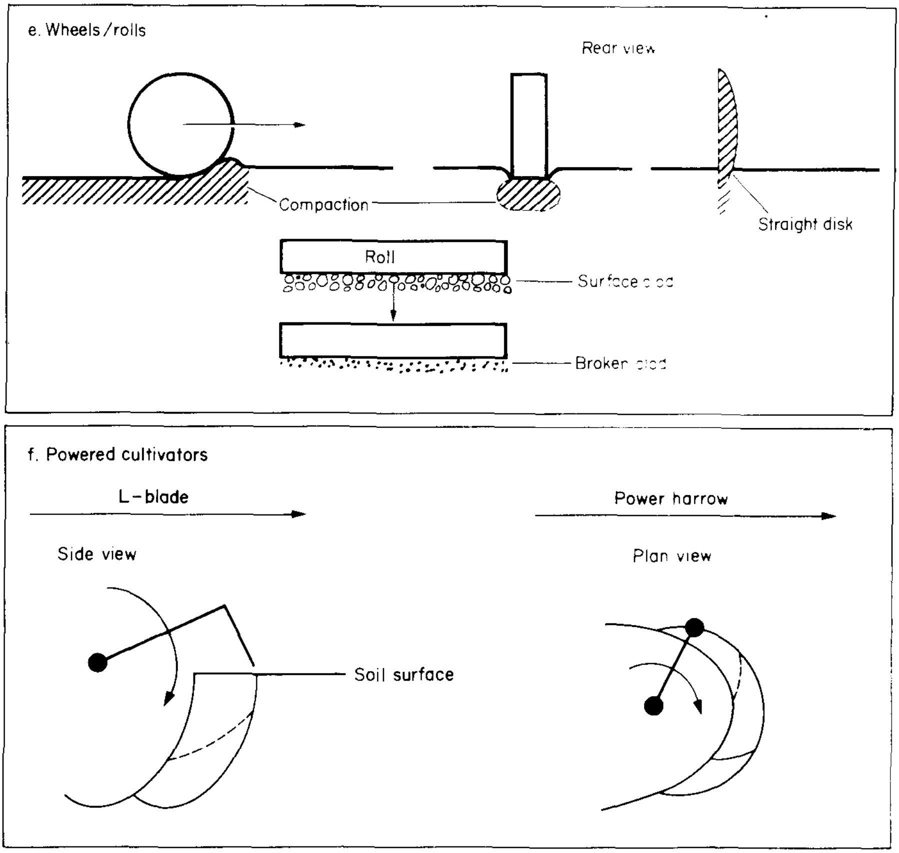
Group	Example
Wide tines (working width greater than working depth)	Leveling blades Wide chisel tine plows Angled disk harrows Subsurface sweeps and blades
Narrow tines (working width less than working depth)	Cultivation tines Tiller tines Narrow chisel tine plows
Very narrow tines (working width much less than working depth)	Harrow tines Mole plows
Sideways angled blades	Moldboard plows Disk plows Disk harrows
Wheels/rolls	Plain, peg tooth, crumbler rolls Presses
Powered tines	Horizontal-and vertical-axis powered rotary cultivators

The initial action of the implements and the resulting soil disturbance are shown in Figure 5. In addition to initial soil disturbance, further breakdown may occur if the implement throws the loosened soil. The degree of subsequent breakdown depends on the soil's impact velocity.

Although tined implements are separated in Figure 5 into three general groups, the disturbance caused by a given tined implement could fall into any category, depending upon soil conditions. As tine working depth increases in a given soil, the nature of the soil disturbance changes from that of a wide to a narrow to a very narrow tine (5).

The transition from narrow to very narrow tine disturbance at the critical depth is particularly important. As


a. Wide tines, width >> depth.
Surface
Loosening
Tension crack
Soil surface
Tine, hoe blade, plowshare, sweep
b. Narrow tines, depth > width.
Rear view
Soil wedge
Loosening
Undisturbed soil
Tine
Soil surface
Soil wedge
Rear view
Loosening
Compaction
Rearrangement
d. Sideways angled blades
Plan view
Flow
Plow
Flow
Angled disk



5. Action of various implements and resulting soil disturbances.

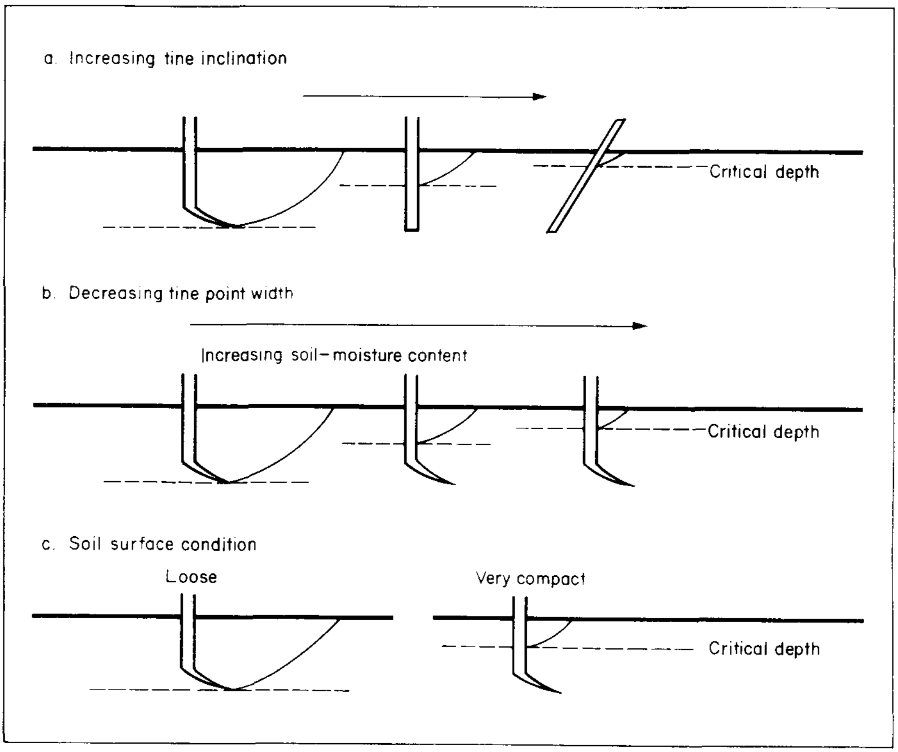
the tine moves below critical depth, the soil disturbance at and below critical depth changes from brittle, which loosens soil, to compressive, which compacts it. The position of working depth relative to critical depth is a major determinant of effective cultivation.

Critical depth and hence maximum and minimum useful working depths for loosening and compression are influenced by implement design and soil factors. Critical depth increases with increasing tine width, decreasing tine inclination, and decreasing soil-moisture content. Loose, weak surface soil over stronger, denser soil at working depth tends to increase critical depth. Conversely, strong, compact soil above weaker looser soil at working depth reduces loosening at depth (Fig. 6).

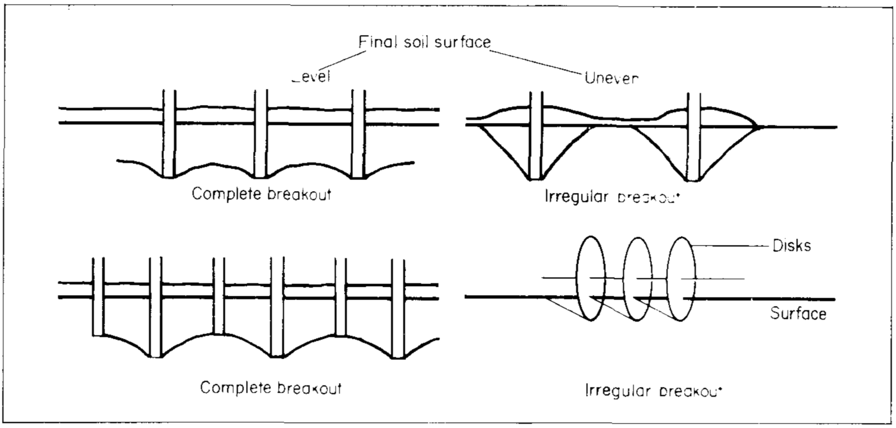
EFFECT OF TINE SPACING AND POSITION ON SOIL DISTURBANCE AND FORCES

The uniformity of soil disturbance with multiple–tine implements depends on tine spacing (6). With narrow tines working above critical depth under upland conditions, tine spacing less than 1.5 times working depth is necessary for complete soil breakout at depth. Wider spacing causes incomplete breakout and uneven soil surface (Fig. 7).

Critical depth for given tines can be increased by first loosening the surface layers. Shallower loosening can be a separate, preparatory, operation or shallow working tines can lead the deep tines on the same tool–frame. Adding appropriately positioned shallow tines (Fig. 8) does not increase draft force. Separate shallow and deep cultivations can halve the maximum pull required, as compared to deep cultivation with no preparatory shallow cultivation.



6. Factors influencing critical depth.

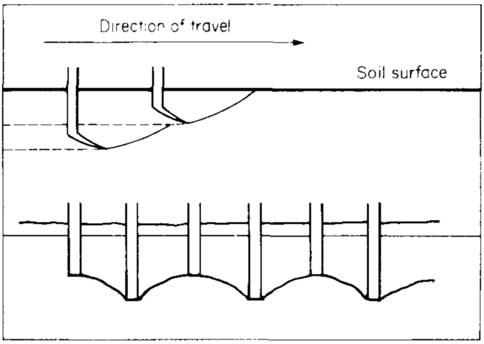


7. Influence of tine spacing on soil disturbance at depth.

SOIL SORTING AND TRASH HANDLING

Small clods and aggregates settle and coarse clods rise during tillage. The greatest separation occurs with narrow tines and the least with powered rotary cultivators, and with moldboard and disk plows.

Forward-inclined tines tend to move trash toward the surface and are easily blocked unless they are well-staggered with the legs swept back from the working tips. Backward-inclined tines and rolling press or disk-type implements move trash to depth and are less easily blocked. Powered rotary cultivators tend to produce more uniform mixing.



8. Soil disturbance with multiple-depth tine combinations.

IMPLEMENT SELECTION FOR BASIC CULTIVATIONS

An implement classification for basic cultivation is as follows:

Task	Implement characteristic
Loosening	Forward – inclined tines at single and multiple depths Plows Powered rotary cultivators
Mixing (on previously puddled soil)	Disk harrows Powered rotary cultivators Chisel tines Plows Peg tooth and crumbler rolls Presses
Inversion	Moldboard plows Disk plows
Compaction by smearing (bottom of puddled layer)	Disk harrows Backward – inclined tines Powered rotary cultivators
Seedbed compaction (upland soil)	Vertical tines Rolls Presses
Leveling (puddled soil)	Backward – inclined and vertical tines
Clod disintegration (dry soil)	Rolls Disks Powered rotary cultivators

POWER AND DRAFT CAPABILITY FOR TILLAGE

All implements have minimum draft and power requirements that are determined by soil conditions, implement geometry, working depth, and speed. Some implements are unusable in certain situations. Animals, representing low draft power, can sustain an average continuous pull of 10-15% of their body weight. For short periods, with adequate rest, they can pull up to 5 times that. A single, medium-sized buffalo can sustain a draft force of about 1 kN.

On dry upland soil conditions, tractors can pull about half their weight. In rice fields, where tractors obtain support and traction from the pan at the base of the puddled zone, the pull may be less. This is because the pan's support capacity limits tractor weight and pressure, and therefore, traction. Additionally, the pan may be destroyed by excessive tractor-wheel slip or by drivewheel penetration, thereby causing serious problems. Moreover, powered implements that develop a forward thrust do help overcome traction problems.

Where the minimum draft requirement exceeds available draft or tractive force, tillage sometimes can be completed in stages that each have sufficiently low draft requirement. Implements that can work progressively deeper at each pass also can help.

In lowland rice fields, substantial thrust can be achieved only by using the strength of the base pan or compacted zone. Implements such as seeders, planters, and fertilizer applicators are frequently ground-driven; therefore the drive wheels must develop a thrust force at constant working speed. This can be achieved using a wheel with spikes that extend through the puddled soil into the underlying compact layer. When very little forward thrust is needed, paddle-wheels working in the puddled soil may be adequate.

IMPLEMENT DESIGN AND SELECTION

Land preparation systems for lowland rice have been described by De Datta et al (1). The following are examples of one approach to selecting the most appropriate implements for specific soil manipulations. The chosen implement not only should produce the desired result, but also should minimize draft and power demand of the available power unit.

1. Initial loosening and weed control in dry soils.

   Field requirement: to loosen soil to a specific depth and incorporate trash and residues.

   Basic cultivation requirements: loosening, and inversion or mixing.

   Soil working conditions: soil moisture may be close to plastic limit or drier, Draft requirement increases with decreasing moisture content, particularly in finer-textured soils. Varying amounts of organic matter: some of which is loose, some attached to soil aggregates.

Implement requirement: moldboard or disk plows, which can loosen the soil and bury almost any amount of trash. However, they have a high unit draft requirement, and disk plows are not particularly suitable for animal operation. Forward-inclined tined cultivators are suitable for loosening and for handling small quantities of short trash; their unit draft force is low.

2. Puddling.

Field requirement: to puddle soil to the appropriate depth, giving a compact, low permeability layer at its base that minimizes percolation and supports field traffic.

Basic cultivation requirement: mixing and incorporation of organic matter; compaction of pan by smearing; hydraulic sealing, without increasing pan depth.

Soil working conditions: very wet soil, with little strength, easily disintegrated and dispersed when loaded by almost any implement.

Implement requirements: implements that readily penetrate the puddled layer, carry organic material downward, and compact and smear at depth. Backward-inclined narrow tines, disks, and presses perform well, but need large forces. Powered rotary cultivators are also effective and have fewer draft problems. Forward-inclined tines increase the risk of excessive penetration, and incorporate organic matter poorly. Heavier implements require accurate depth control and should be used in combination with crumbler or paddle roll implements.

3. Seedbed preparation and deep soil loosening for crops following rice in puddled soils.

Field requirement: to alleviate soil compaction in deeper soil layers, and to prepare an appropriate seedbed. Tillage must be achieved with minimum moisture loss.

Basic cultivation requirements: loosening, clod disintegration, and seedbed compaction.

Soil working conditions: high moisture content, particularly below the compacted pan at 200-300 mm depth. Surface layers dry rapidly, causing increasing bulk and clod strengths that make clods hard to break. Deep-loosening implements may be working below their critical depth.

Implement requirements: deep-working wide tines, or shallow tines giving a preparatory loosening of surface layers in a two-stage narrow-tine deep loosening that has lower draft requirement. Combined shallow and deep loosening is better, and the shallow loosening should be with tines or a powered rotary cultivator. The main target in the shallow-loosening stage is the pan, which limits loosening by preventing upward movement of the wetter, deeper soil.

Traffic for seedbed preparation after deep loosening will rapidly recompact moist, loose soil. One solution is to prepare the seedbed, deep-loosen, drill seeds, and compact the seedbed in one pass, thereby avoiding subsequent traffic. Alternatively, traffic might be controlled and, if possible, restricted to sacrificial traffic lanes between which the crop is grown. In upland soils the drier traffic lanes allow access to cultivate the .cropped soil at much higher moisture contents than with random traffic access. In consequence, brittle loosening and clod disintegration with a powered rotary cultivator can be undertaken at these higher moisture contents.

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SIMULATION MODELS FOR TILLAGE AND SOIL PHYSICAL VARIABLES

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Abstract

The objectives of modeling tillage operations and soil physical variables are discussed, Existing models and theories suitable for use in modeling are reviewed. Methods for measuring soil properties relevant to tillage and for obtaining suitable data for future models are outlined. The development at the University of Melbourne of a tillage/water balance model for wheat cropping is described.

SIMULATION MODELS FOR TILLAGE AND SOIL PHYSICAL VARIABLES

In almost all tillage and soil research, the parameters being studied are complex and dynamic. Soil properties vary substantially over depth, time, and with different management practices and sites. Therefore, tillage research has concentrated on the overall effect of different options on crop performance. Controlled plot experiments have predominated and yield differences have been assessed as if only tillage inputs were relevant.

The results of plot trials are site-specific and conflict at different locations (20). Hence it is difficult to extrapolate the results of plot experiments to other areas or even to apply them under different weather conditions at the same site.

A mathematical model for a wide range of sites and conditions can be developed. By using suitable, process-based computer models, the extent and duration of plot trials can be reduced, They also allow the extrapolation of research results across geographical areas. Models also help interpret and understand plot results. The need to understand the processes to be simulated also ensures that research programs are efficiently planned.

This paper describes computer simulation modeling as a complementary tool to plot experiments that avoids some of their limitations. Computers also have potential for passing results of research and technology to farmers. These points are illustrated by the SIRAGCROP project for irrigated agriculture in Australia (6).

SIRAGCROP is being established to advise farmers on management systems and associated information models to help them improve yields and water use efficiency through better management. The system operates from a central computer with telephone connections to individual farms. Advice includes optimum timing for preplanting irrigation, fertilizer and herbicide requirements, disease prediction, irrigation scheduling, and financial returns on water and application costs.

Surveys of farming practices and research projects provide data for the models. The research projects include work on required land slopes, irrigation scheduling, root zone limitations to plant growth, carbon balance and water use, diseases of irrigated wheat, efficiency of N use, genotypes and sowing dates, wheat breeding, crop rotations, LANDSAT studies, and farm and market economics. Although SIRAGCROP has a wider scope than a tillage-soilmodel, it does illustrate the potential of modeling.

Separately, a composite model for dryland wheat is being developed (15). Its core model consists of daily water balance and crop growth components. Subprograms will be appended when more detailed simulation of site-specific or particular conditions are needed. Submodels will include routines for N, P, soil temperature and frost, erosion, tillage, root growth, weed growth, and diseases.

A tillage-water balance submodel, the Melbourne University Tillage Simulation (MUTS) model, also is being developed. It will simulate soil temperature, infiltration and redistribution of soil water, and soil physical properties as influenced by tillage, and will stand alone or act as a subprogram to the core model,

Although MUTS is for wheat, with appropriate modifications the processes would be applicable to rice and rice-based cropping systems.

OBJECTIVES OF TILLAGE MODELING

Objectives must be clearly identified before a model can be selected or developed. Suitable objectives of tillage modeling are to

- reduce the number of plot trials needed to evaluate the effect of different tillage options on soil properties;
- extrapolate existing plot results to other soil and weather conditions;
- identify tillage processes that require further research; and
- evaluate quickly optimum tillage requirements for crop growth under specific soil and weather conditions.

Additionally, the model output must be specified. For tillage modeling, soil condition usually is of primary interest, and variables that influence plant growth and development should be selected for output. Parameters listed by Collis-George and Lloyd (5) were moisture, aeration, temperature, and bulk shear strength; they should all be simulated in relation to the cultivated layer. Because soil macrostructure directly affects root and shoot growth, it should be an output parameter.

A model should also

- be reliable and user friendly;
- have wide application;

- be based on physical processes rather than empirical relationships;
- require little field data to operate; and
- be versatile and account for varying crop management practices.

Some tillage research emphasizes the dynamic processes occurring between the implement and the soil. These studies eventually should enable the final soil condition to be simulated through the actual failure mechanisms. Meanwhile, empirical relationships between the tillage operation and the resulting soil conditions must be used. At least two ways of simulating tillage fulfill these requirements:

- simulated soil properties can be altered on a given day by amounts preset for each tillage operation; or
- existing soil conditions and tillage variables can be used to predict the final soil condition for each tillage operation based on previously developed relations.

The second approach has greater potential in tillage modeling because the relations become less site-specificas they are improved. Field work at the University of Melbourne is planned to provide sufficient data to develop the relations for MUTS.

Regardless of the simulation approach, a model also must allow for weather-caused soil changes. Effects of weather are best adjusted at daily intervals. Shorter intervals may be necessary during major changes such as high intensity rainfall.

EXISTING MODELS

The following are examples of tillage models or theories from which good models could be developed. Porter and McMahon (20) and McMahon (15) provide more extensive treatments.

Composite models

The most comprehensive model of crop growth, water balance, and tillage is the Nitrogen-,Tillage-, Residue-Management model (NTRM), developed for maize in the United States. The model simulates physical, chemical, and biological processes in the soil–water–crop continuum using integrated submodels for crop residues; soil temperature; soil carbon and N transformations; interception, infiltration and unsaturated flow of water; evaporation and transpiration; solute transport; crop and root growth; chemical equilibria processes; and tillage. There are 111 interrelated subroutines in the program.

The tillage component of NTRM incorporates 14 subroutines that allow modification of soil physical, biological, and chemical properties that affect crop yield (Table 1). The properties are transformed in either of the following ways to simulate a tillage operation.

- The user specifies changes in soil properties by feeding in tillage date and type, depth, and soil properties.
- Only tillage date and type and depth are fed in. The tillage submodels then estimate the changes in soil properties using appropriate equations.

NTRM is similar to SIRAGCROP in that it combines the results of work in many disciplines for use in research, extension, farmer, or engineering applications. NTRM has a broader base than SIRAGCROP and is much larger than the proposed SIRAGCROP model. Its size and complexity make it unsuitable for simple modification for other crops and for research or extension use in an abbreviated form.

DeCoursey (7) described a composite model for cotton. Unfortunately it was developed only to demonstrate the capability of composite models and was not documented for subsequent users (DeCoursey, pers. comm.).

Table 1. Tillage-associated soil properties used in NTRM model (21).

Physical properties	*Biological properties*
Soil bulk density	Carbon and nitrogen transformation rates
Soil water characterization curves	Microbial mass and distribution
Soil water holding capacity	Root mass and distribution
Soil infiltration rate	
Random roughness	*Chemical properties*
% Residue cover	Organic matter
Soil strength	Residues NO_3-N and NH_4-N
Soil water content	Major cations and anions
	Cation exchange capacity
	Solid phase salts
	Exchangeable ions

Soil-water modeling

Soil-water modeling has been examined in detail. The infiltration process can be described by the empirical equations of Kostiakov (14), Horton (12), and Holtan (11), or based on the theoretical equations of Philip (19), or Green and Ampt (9). Infiltration in Philip's equation is expressed as a function of time. Green and Ampt express infiltration as a function of soil-moisture content. Many process-based models use one of these equations.

A larger number of available empirically based water-balance models assign a water-holding capacity to the soil being studied. But they are unsuitable for a process-based, tillage-sensitive model of soil moisture where the time interval of modeling may be much shorter than 1 d.

Mein and Larson (16) developed a two-stage model to simulate infiltration before and after surface ponding. The first stage predicts the volume infiltrated to the moment at which ponding begins. The second stage is a modification of the Green-Ampt model that allows for the infiltration volume before ponding. Moore et a1 (17) evaluated this model, named it GAML, and concluded that it performed well although some of the parameters, such as air entrapment and surface sealing, had to be modified for field conditions. Idike et a1 (13) compared GAML to Holtan's model and with experimentally determined infiltration rates. Both models produced good results, but the Holtan model did not correctly predict the time to ponding.

GAML allows for the effect of surface microrelief (roughness) on infiltration and runoff, making it particularly adaptable for tillage modeling. It has been adopted for MUTS. Field work is underway to establish suitable microrelief predictive relations for several tillage options.

Redistribution of soil water after infiltration has to be simulated. This may be done through Darcy's equation for unsaturated flow combined with the equation of continuity to give Richard's equation. Amerman (1) developed the method of finite differences for solving the steady-state, two-dimensional form of this equation using the successive over-relaxation method. He found the method suitable for a wide range of geometric shapes, hydraulic boundary conditions, and soil-water distributions. Unsaturated or saturated flow regions, or those containing phreatic surfaces. also can be modeled using this technique. It is, however, complicated and requires computing expertise.

Soil–structure modeling

Soil structure significantly affects root growth. Slack et a1 (23) developed a model to describe soil–wateruptake by plant roots as a function of plant and soil parameters. It performed satisfactorily, although difficulties were reported in estimating soil–watercharacteristics and conductivity for dry soils. Although techniques are available for estimating these parameters (3), the effect of soil structure on plant growth needs to be better modeled.

The measure of soil macrostructure developed by Dexter (8) is useful for tillage models. It quantifies soil structure more readily than traditional methods that use associated properties such as bulk density or penetration resistance.

The method involves impregnating an in situ tilled soil with epoxy resin. When the resin sets, the resulting block of soil is sectioned with a diamond saw. At 1-mm intervals, the voids are coded as 1 and the aggregates as 0 to evaluate the soil structure at different layers. The resulting strings of codes are analyzed to determine a statistical distribution of the macrostructure. The method is expensive because each sample requires 2 to 3 kg of epoxy resin. In Australia, the resin costs about US$5/kg. However, the method does provide a quantitative measure of soil macrostructure at distinct depths in the plowed profile, and is potentially useful in tillage models. This soil–microstructure parameter will be included in MUTS.

Evapotranspiration modeling

Evaporation and transpiration usually are incorporated in crop growth rather than tillage models, and as such are outside the scope of this paper. However, evapotranspiration does affect water balance and should be an integral part of any tillage model. For rice fields in tropical Asia, Yoshida (27) proposed a simple evapotranspiration model based on solar radiation:

$$E = 0.0105\ S$$

where E is cumulative potential evapotranspiration in mm and S is cumulative incident solar radiation in cal/cm^2. This model's predictions agree with measured evapotranspiration from rice fields in tropical Asia; the model is presumably effective because of the low prevailing wind conditions in that region.

This review of available simulations, particularly with respect to soil-moisture simulation, shows there are ample data available to develop a useful tillage-soil mathematical model. The inadequately defined parameters such as bulk density, soil strength, and soil macrostructure, which are dynamic in field situations, can be simulated with empirical relations derived from existing data until more exact procedures are available. To develop suitable relations, a data bank for soil and tillage should be established.

BASIC DATA REQUIREMENTS

A data bank should contain those variables needed to describe the actual tillage operation, soil composition and physical properties, other soil factors that affect plant growth, and climate.

Tillage

Implement draft, speed, working width and depth, and soil disturbance achieved are required to classify a tillage operation. Measuring draft and speed is straightforward. Draft usually is measured by a load cell between the implement and the traction device. If available, a simple microprocessor-based integrator and data logger may be connected to the load cell to calculate and record average loads. Speed can be measured by timing the implement over a set distance.

Measuring working depth and soil disturbance is more difficult because of surface microrelief and lack of a precise depth control on most implements. Although sophisticated methods such as radar are being investigated to accurately measure depth, they still are developmental. Therefore, working depth should only be used to indicate the type of operation. Draft, unit width, and speed should be sufficient to develop empirical relations between tillage operation and soil properties.

Soil physical variables

Surface and subsurface soil properties must be quantified before the pre- and posttillage processes can be simulated.

The surface is represented by its microrelief. Subsurface properties, defined for the whole profile, should include mechanical composition, moisture-characteristic curves, infiltration behavior, macrostructure, bulk density and porosity, and bulk shear strength.

Of these variables, mechanical composition can be obtained using well-established laboratory tests. Moisture-characteristic curves can be determined over a range of soil suctions from 0 to 1.5 MPa (pF = 0 to 4.2) using porous ceramic plates in pressurized cells. Hamblin (10) tested and advocated the use of No. 42 Whatman filter paper to determine the moisture characteristic curve for soils in situ. Where many soil samples are taken, this method provides a satisfactory alternative to other methods. Unfortunately, it takes more time than the pressure cell method.

Infiltration parameters are difficult to quantify despite the availability of suitable equations. One approach is to calculate infiltration using a laboratory value for saturated hydraulic conductivity. Although this approach is particularly suited to simulation because of its mathematical nature, it ignores the effects of surface crusting and trapped air. Some equations are better able than others to accommodate these effects. GAML does so by modifying the values used for hydraulic conductivity, average suction at the wetting front, and initial moisture deficit (17).

Soil bulk density and bulk shear strength often are represented by cone penetrometer readings on the assumption that the force required to push a probe into the ground is not only some measure of the soil strength but also represents the forces exerted by a growing root tip.

In fact, the penetrometer measures a combination of the cohesive and frictional properties of the soil. Mulqueen et a1 (18) found penetrometer results ambiguous for field soils where moisture content, bulk density, shear strength, and structural state vary sharply with depth. The effects of compaction ahead of the probe and soil-shankfriction caused the cone index measured at a particular depth to differ from the true index at that depth. They concluded that penetrometers only are useful for comparing strengths of soils of similar moisture content and structure. Where a particular strength variable such as shear strength or bulk density is needed, it should be obtained by direct measurement. This finding is especially relevant to tillage modeling, where structure, density, and moisture content all can vary widely with time and depth. Consequently, penetrometers should not be used to obtain data on bulk density and soil strength for tillage modeling.

Many methods have been used to measure bulk shear strength. They include the triaxial cell, direct shear box, torsional shear box, shear annulus, and shear vane. Stafford and Tanner (25) compared these methods for six different soil types and found that they gave different values of cohesion and friction angle. They concluded that the proper test method depends on the particular purpose for which the shear strength is required. For in situ soils, a shear annulus should be used. They gave a design for an apparatus operable by one person.

The torsional shear box was successfully used in Australia by Collis-George and Lloyd (4) to classify the soil strength profile in seedbeds. Their hand-held box is easier to use than the Stafford and Tanner annulus (25) and accurately measures the shear strength of the surface soil layer where normal stress is negligible. The torsional shear box is better than a shear vane because the friction angle can be obtained to give a full Mohr-failure envelope for the soil. If the friction angle must be calculated for many soils, the annulus design (25) would be easier to use and would provide more reliable results than the shear box. The hand-held shear box was adopted for MUTS because measurements only are taken in the cultivated layer.

Most methods for measuring microrelief depend on a series of drop-pins that show a surface profile transect (2). If a row of drop-pins is moved along the plot, a two-dimensional grid of the surface is obtained. The heights of the pins for each profile can be recorded manually, photographically, or electronically. Surface microrelief is computed, usually as a function of the standard deviation of the pin heights, although Burwell et al (2) recommended using the standard error of the logarithm of the pin heights.

At the University of Melbourne a drop-pin configuration similar to that described by Burwell et al (2) is being used to photograph the effect of different tillage operations on grey clays. A 50-mm grid over a 1-m square is adequate to measure surface microrelief.

Other data

Other data necessary for developing or operating models of tillage-soil interactions include meteorological data, soil moisture, and soil temperature. Of these, meteorological data usually are the most readily available. Daily values of rainfall, maximum and minimum air temperature, and pan evaporation are a minimum data set. Some models may need shorter-interval rainfall information. If plaviograph data are unavailable, there are techniques to synthetically generate short-interval rainfall (24).

Daily average windspeed, radiation, and wet and dry bulb temperatures are used in combination equations to estimate actual daily evaporation. These estimates are more realistic than pan evaporation measurements. Soil moisture values are needed to validate moisture-balance submodels. These values usually are measured gravimetrically by drying and weighing samples, or with a neutron moisture meter at regular intervals.

Soil temperature affects seed germination, plant emergence, root growth, nutrient uptake, and plant development. Because soil temperature is affected by tillage, it is an important variable in tillage modeling. There are several models that simulate soil temperature from other meteorological and soil property inputs, but they need actual data for validation.

Soil temperature often is recorded with mercury-in-glass thermometers at meteorological sites at set times of the day. It is better to record hourly values using thermocouples or transistor probes and electronic data loggers. Such probes must be placed at precise depths: especially in the top soil layer where there are strong temperature gradients. In the top 50 mm of soil, a 1 mm error in placing the probe can cause a large error in recorded temperature (26). It is also necessary to use enough probes at each depth to estimate the spatial variation in temperature, which is influenced by the variability of soil physical conditions and crop cover.

DATA VARIABILITY

Variability in measured values of soil properties depends on the particular soils and on the instruments and methods used. Measurements of shear strength are subject to both of these sources of variability. To be widely applicable, the model should use reliable data. Tillage researchers should monitor as many as possible of the pertinent variables to establish a suitable data base, and methods of measurement should be standardized. All measurements should be sufficiently replicated to allow calculation of confidence limits. For some soil properties, a log-normal rather than a normal distribution may be more appropriate (22).

CONCLUSION

This paper argues that mathematical models can be used in tillage research to reduce the extent and duration of plot trials and to assist in interpreting and extrapolating results. Their desired characteristics can be identified in existing models. Moreover, basic data still are needed to validate models for specific locations and to develop empirical relations to predict soil properties. Appropriate variables have been listed, and comments made on methods for their measurement.

Future tillage work relating to rice should be planned to allow results to be used in deterministic simulation models. The following variables should be monitored: implement draft, speed, working width and depth and soil disturbance achieved, soil type and textural composition, moisture characteristic curve, infiltration capacity, macrostructure (and surface glazing), bulk density (and porosity), bulk shear strength, surface microrelief, soil moisture and temperature, and weather data. At least one trial site should be established to monitor these variables on a representative soil using a range of tillage methods.

Additionally, a research program should be established to collect and collate tillage research results from rice-growing countries. The program would need to be undertaken by an organization having adequate computing facilities and the capability to develop tillage–soil–weather simulation models for rice–based cropping systems.

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SOIL - WATER MANAGEMENT IN RAINFED RICE - BASED CROPPING SYSTEMS

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Abstract

Soil–water management is crucial to rainfed rice–based cropping systems because of uneven monsoon rains. An integrated strategy for maximizing crop production in drought–prone areas must consider agroclimatic conditions and a combination of soil and agronomic management practices. Crop scheduling based on rainfall pattern determines cropping intensity and drought and flood avoidance. Bunding, puddling, soil amendment, and subsurface barriers help reduce water requirements for lowland rice. Ridge–furrow cultivation systems can save dryland crops from excess water damage, and rain harvesting and runoff recycling can minimize the risk of drought. Appropriate tillage, mulching, and fallow land management significantly reduce evaporation. Agronomic practices suited to individual crops in a cropping pattern can increase water use efficiency of both rice and dryland crops.

SOIL-WATER MANAGEMENT IN RAINFED RICE-BASED CROPPING SYSTEMS

Nearly 60% of the world rice area is in South and Southeast Asia. Three-fourths of the Asian ricelands are rainfed. In India, 65% of the rice area is rainfed (10) and 89% is rainfed in Bangladesh (Table 1). On most of this land, drought is a major hazard. Lack of drainage and appropriate water management also are serious problems. Rains are so uneven that a single crop may experience both drought and flooding. Knowledge of lowland soil-water retention and movement is necessary for proper soil management, yet little such information is available for soils of rice-based cropping systems (13). Information also is lacking on crop-available water in different soils, and on soil water depletion patterns for different crops (22).

RAINFED RICE-BASED CROPPING SYSTEMS

There are three categories of rainfed rice systems: upland, lowland, and deep water. About 75% of rice is grown on lowlands, and 30% of that is rainfed. Upland rice comprises 10% and deep water and floating rice 15% of world rice area. Upland (dryland) rice is grown on unbunded fields with dryland preparation. The fields are never flooded artificially. Lowland (wetland) rice is bunded. Land is prepared wet or dry and flooded with less than 1 m of water. Deep water rice is grown where flooding depths exceed 1 m. Seeds are usually broadcast on dry soil.

Upland rice-based cropping systems

The largest areas of upland rice are in India, Indonesia, Thailand, Bangladesh, Burma, and the Philippines. Growing-season rainfall in these areas varies from less than 600 mm to more than 2000 mm. The most common range is 1,200-1,500 mm. Some upland rice areas support a single rice crop, but most are planted to one or more dryland crops. They are mixed-cropped, relay-cropped, or sequentially cropped with upland rice. Common cropping patterns (- = sequential cropping, + = intercropping, / = relay cropping) are rice - maize, maize + rice - maize, cassava + maize + rice - legume, rice - maize / peanut.

Most Asian upland rice is planted on Ultisols and Alfisols. Soils usually are light-textured and have poor water holding capacity. In tropical Africa and Latin America,

Table 1. Irrigated and rainfed rice area in some countries of South and Southeast Asia (10).

Country	Rice area (million ha)			Rainfed area (%)
	Total	Irrigated	Rainfed	
India	39.0	13.5	25.5	65
Bangladesh	10.0	1.1	8.9	89
Thailand	8.7	1.2	7.5	86
Indonesia	8.2	5.2	3.0	37
Burma	5.3	0.9	4.4	83
Philippines	3.5	1.5	2.0	57

upland rice is commonly grown in shifting cultivation systems on sloping, coarse-texturedsoils. Shifting cultivation leaves soil inadequately covered during rainy season, thus causing excessive soil erosion.

Upland rice commonly suffers from drought in Asia and especially in Latin America and Africa. On sloping land, poor water holding capacity of the unbunded, coarse-textured soils favors drought stress soon after rains stop. On flat areas and lower slopes, moisture conditions are more satisfactory for upland rice. In Africa, upland rice grows well on hydromorphic land primarily because of the favorable moisture regime.

Lowland rice-based cropping systems

Rainfed lowland rice areas have four rainfall regimes: premonsoon moist, wet monsoon, postmonsoon moist, and dry seasons. Lowland rice is grown in the main monsoon when water is most abundant. Dryland crops are grown in pre-and post-monsoon when rainfall is unpredictable. Some common cropping patterns are rice - fallow, rice - rice, maize (or beans) - rice, rice - wheat, rice - mungbean (or cowpea, chickpea, lentil), and rice - wheat - maize.

In premonsoon periods, crops are prone to drought stress at early growth stages. Drought is caused by late rains and an initially dry soil profile. Crops may be flooded at later growth if heavy rains are early and soil is poorly drained. Lowland rice grown on well-drained soils (such as Udalfs and Udults) often suffers alternating drought and flooding during the monsoon. Postmonsoon upland crops frequently are damaged by excess water at crop establishment and drought stress at later growth stages.

CLIMATIC FACTORS

Variabilities of onset and duration of rains, and of length of wet and dry periods within the cropping season, are important to rainfed rice-based cropping. In most rainfed rice areas, average total rainfall is ample for crop growth. But, rainfall distribution may be a major limiting factor to crop production. Rainfed lowland rice grows best on land that receives not less than 200 mm of rainfall/mo for a minimum of 3 mo. There should not be more than 7-10 d between rainfall. The 200 mm/mo estimate assumes 6-7 mm potential evaporation/d. Daily rainfall is actually more critical for upland rice than monthly or seasonal rainfall. Moisture stress can damage or kill plants in an area that receives 200 mm of rain in 1 d, and receives none for the next 20 d. An evenly distributed 100 mm/mo is better than 200 in 2 or 3 d. Matching duration of crop and variety with the appropriate rainfall regime increases productivity per unit area and time.

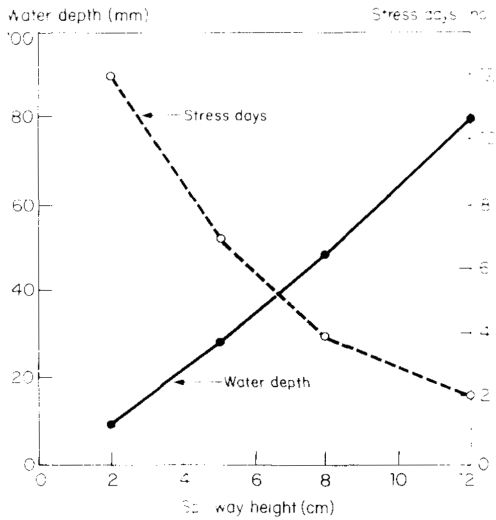
SOIL MANAGEMENT FOR WATER CONSERVATION

Soil management practices to minimize water loss include bunding, puddling, compaction, creating a plow pan or subsurface barrier, and adding bulk materials.

Bunding

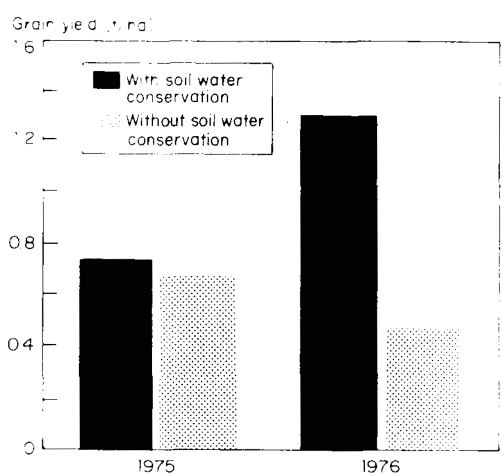
Farmers in rainfed rice areas stabilize bunds to reduce seepage. When the monsoon begins, bunds are repaired or rebuilt and the inner faces are lined with clay mud to reduce leakage. Bund and spillway height usually are increased to impound extra rainwater. In a simulation study with 11 yr of daily rainfall data for Cabanatuan City in Central Luzon, Philippines, Bhuiyan et al (1) observed that each increase in spillway height from 2 to 5, 8, or 12 cm increased field water depth and consequently reduced the number of water stress days during crop growth (Fig. 1). They also found that, with less than 10 mm daily rainfall, all rainfall was kept within the bunds with spillways 2-12 cm high. When rainfall intensity increased above 10 mm/d, however, effective rainfall decreased for all spillway heights. The decrease was less with higher spillways.

Water conservation measures such as bunding, deep tillage, and mulching increase upland rice yields. Traditionally, however, farmers leave their land unbunded, unstumped, and unfertilized, and follow improper tillage practices.



1. Simulated effect of spillway height, number of stress days, and water depth in a bunded rice field in Jun-Sep for 11 yr (1964-74). Cabanatuan, Central Luzon, Philippines (1).

Mahapatra and Patnaik (16) reported that in Sierra Leone, upland rice yields tripled when soil and water conservation measures were adopted on sloping land (Fig. 2). They also found that plowing increased yield on bunded fields on sloping land. On unbunded fields, no-tillage treatments yielded better, perhaps because soil erosion was less than on plowed fields. Erosion is a major problem in Africa and Latin America. Bunding and leveling can substantially reduce erosion in those areas.



2. Mean grain yield of upland rice with and without soil-water conservation measures on a farmer's field at Mkassa, Sierra Leone (16).

Puddling

Puddling breaks down large soil aggregates, destroys noncapillary pores, reduces apparent specific volume, and increases microvoids (6). A puddled soil retains more water than an unpuddled soil at similar soil moisture tension. Because puddling reduces noncapillary porosity and increases bulk density, hydraulic conductivity and percolation substantially decline. Evaporation and drainage from puddled soil is markedly less than from the same soil in an aggregated state (3). Puddling lowland rice fields is beneficial in rainfed areas where drought commonly reduces yield.

However, puddled soil is unfavorable for dryland crops following rice. The slow water loss from puddled soil limits early seedbed preparation and establishment of dryland crops. When puddled soil dries, bulk density increases, infiltration rate decreases, aeration declines, and soil impedance to root growth rises (20). The adverse effects of puddling are more severe in light-textured soils because they tend to compact more easily. Sur et a1 (21) reported that a restrictive plow pan with increased bulk density and reduced hydraulic conductivity formed at 15-20cm depth in a puddled sandy loam after 6 yr of a rice - wheat rotation. Root growth and water storage were less on that soil than on the same soil planted to a maize - wheat rotation. Puddling usually does not form plow pans on clay soils. In soils with plow pans or where shallow hardpans occur, deep plowing and subsoiling may increase soil water storage and promote root penetration.

Soil amendments and subsurface barriers

Various subsurface barriers and soil amendments have been tried to control percolation in lowland rice fields. Bentonite has been incorporated in the top 25 cm of soil to reduce percolation (5). The necessary amount and frequency of such amendments vary with their residual effect and soil characteristics. Rao et al (19) used subsurface barriers of bitumen and cement and found that water required for growing rice was substantially less than in the control (Table 2). Similarly, Pande (18) observed that percolation on lateritic sandy clay soils was negligible with subsurface barriers of asphalt, bitumen, cement, or polyethylene sheets, but was as high as 100-120mm/d without subsurface barriers.

Table 2. Influence of subsurface barriers on crop and percolation water requirements of dry season and wet season rice crops (19).

Subsurface barrier treatment	Water used (mm)	
	Dry season	Wet season
No subsurface barrier	3173	706
Bitumen (80/100) 5 mm at 30-cm depth	965	485
Bitumen (80/100) 5 mm at 40-cm depth	869	472
Cement layer (5 mm) at 30-cm depth	854	472
LSD (.05)	165	56

Water harvesting and erosion control

Depending on soil and rainfall characteristics, 10-14% of total rainfall can be lost as runoff. Water can be harvested in dugout ponds and used to prevent crop failure during critical water stress periods. Runoff recycling is very important in dry–wet rainfed lowland rice where it is necessary to minimize moisture deficiency in the dry–seeded crop and convert the land to a wetland system later in the season. Ridges and furrows formed before sowing, or cultural operations after seeding, can be used for in situ water harvesting.

Sorjan

A ridge–furrow cropping system called Sorjan is popular in Java and tidal Indonesia, particularly near cities. Raised beds about 3 m wide alternate with furrows that vary in depth and width depending on flooding depth during rainy season. The raised beds provide adequate drainage for high–value upland crops. Rice is grown in the ditches, which act as water reservoirs during drought. Land preparation and rice planting can be advanced because water accumulates quickly in the smaller area. On poorly drained lands where dryland crops predominate, raised beds, ridges, or mounds are commonly used for root crops (4).

Evaporation control

Water conservation involves maximizing rainfall infiltration and storage while minimizing evaporation not related to crop yield. Soil-water conservation practices include tillage, crop residue management, mulching, and fallowing.

Evaporation from a saturated soil occurs in three phases (15), and the particular evaporation phase determines the appropriate method of reducing bare soil evaporation (9). In constant rate evaporation, meteorological and surface conditions dominate. Surface mulches can be used to retard evaporation.

In falling-rate evaporation, water supply to the surface is determined by profile transmission characteristics. Deep tillage modifies the soil-water diffusivity of the profile and hence reduces this second stage drying. Tillage often speeds drying of the tilled layer, but also can reduce water movement from subsurface layers. The net effect of tillage on storage depends on the duration of the process; the depth, degree, and frequency of tillage; subsequent rainfall amount and timing; and the influence of rainfall on reconsolidation (9). A two-layer system with a coarse layer of large pores overlying a finer profile is ideal for controlling evaporation and infiltration. Hillel and Hadas (8) recommended surface aggregates of 0.25-2.0 mm diameter to retard evaporation from bare soil.

In the slow-rate or vapor-diffusion stage of evaporation, water transmission through the dry surface layer occurs primarily through vapor diffusion.

Tillage. Zero and minimum tillage reduce crop turn-around time and provide better residual moisture for crop establishment in rainfed areas. Valuable soil moisture for the post-rainy season crop is lost if fields are thoroughly tilled. For mungbean under low rainfall, Herrera et a1 (7) observed highest yield on a zero-tilled treatment. With postemergence rains, however, complete tillage outyielded the no-till treatment. Hundal and De Datta (14) reported that sorghum grown after lowland rice in a clay soil yielded similarly under zero tillage and complete tillage at three water table depths.

Residue mulches. Residue mulches on the soil surface influence soil-water and temperature regimes. Mulching is of little use in rainy season, but benefits dry season dryland crops. Mulching with 5 t rice straw/ha significantly increased water use efficiency, grain yield, and nutrient uptake (Table 3) in rainfed maize grown after lowland rice (11). Residue mulching also conserves water by controlling storm water runoff, increasing infiltration, reducing weed growth, and decreasing evaporation.

Fallow land management

Land management during the dry season fallow is critical to early establishment of the first crop of dry seeded or transplanted rice and annual cropping intensity. In dry season, the primary objective is soil water conservation through evapotranspiration control. An IRRI study (Fig. 3) showed that all weed-free fallow soil management practices conserved significantly more profile water than farmers' practices (12). As much as 25 cm of soil water was lost in the conventional weedy-fallow. The weed-free treatments lost not more than 5 cm of water from the 1.05-m-deep soil profile. There were no significant differences between soil mulching by plowing and rototilling, residue mulching with rice straw, or chemical weed control. However, soil mulch by tillage during the fallow period was preferable because it requires no seedbed tillage at the onset of rains and hence allows early seeding of dry seeded rice or an upland crop. Bolton and De Datta (2) reported that tillage at the end of the previous wet season enabled crop establishment 3 wk earlier than soil preparation at the beginning of the following wet season.

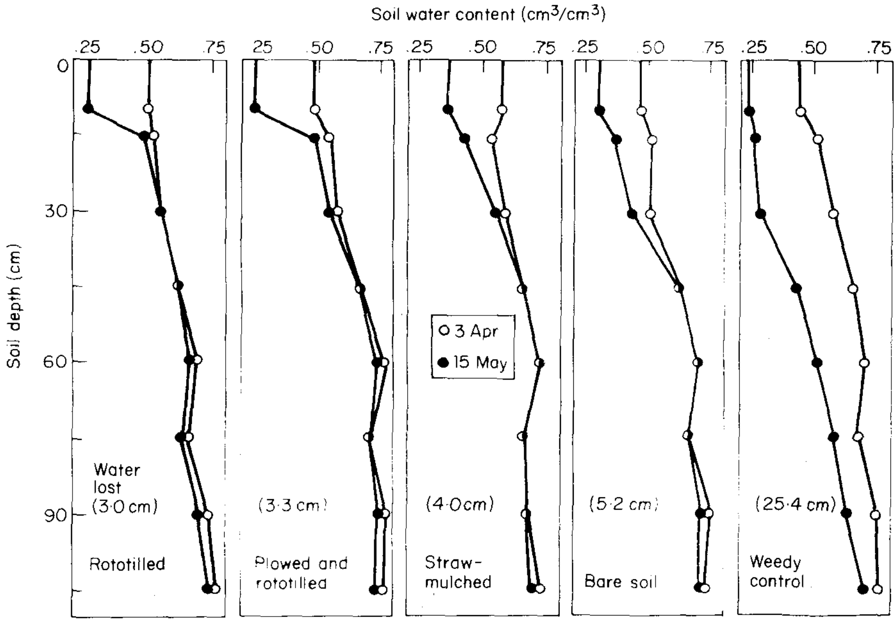
AGRONOMIC PRACTICES

Agronomic practices for rainfed crops should be based upon the annual soil moisture regime. Most lowland ricelands in

Table 3. Effect of rice straw mulch on grain yield, water use efficiency, and nutrient uptake[a] by rainfed maize grown after lowland rice (11).

Treatment	Maize yield ($t\ ha^{-1}$)	Water use efficiency ($kg\ ha^{-1}\ d^{-1}/mm$)	Nutrient uptake (kg ha–1) N	P	K
No mulch (control)	2.0	0.39	46	9	55
Rice straw mulch at 5 t ha^{-1}	2.5**	0.51**	58**	11**	65**

[a] Significant at 5% (*) and 1% (**) levels.



3. Soil water depletion in 6 wk (3 Apr - 15 May) under various dry season soil management systems (12).

India, Bangladesh, Thailand, Malaysia, Indonesia, and the Philippines have the potential to grow two crops. Rice cropping schedules should be adjusted to make the whole system more productive.

Time of sowing is crucial in rainfed farming. In eastern India, early planting (mid-Junto early Jul) of short-duration upland rice at Ranchi and Varanasi facilitates successful cultivation of post-rainy season linseed or chickpea crops. In north India, lentil, linseed, safflower, mustard, gram, barley, or wheat successfully follow lowland rainfed rice. Lentil and linseed are broadcast in the standing rice crop just before harvest. The other crops are grown after tillage following rice harvest. In Malaysia, maize and soybean follow rainfed lowland rice. In the Philippines, a dry seeded rice - transplanted rice sequence is replacing the traditional practice of growing only a single transplanted crop. An analysis of rainfall data for Pangasinan and Iloilo, Philippines, indicated that a dry-seeded rice crop would have 20-30 d of growth before 200 mm of rainfall could accumulate to begin puddling for transplanted rice (17).

Seeding depth in relation to precipitation is another important consideration in growing rainfed crops. Seeds placed too shallow may germinate from a small rain shower, but die unless enough rain falls to moisten the root zone. Deeper seeding usually is best in a dry seedbed.

Other crop management practices for efficient rainfall use include adjustments of planting density and crop geometry, weed control, and efficient fertilizer use. Optimum plant density for rainfed systems is likely to be less than for irrigated crops. Higher plant density produces more foliage and quicker loss of soil moisture through transpiration. Water use efficiency in rainfed areas can also be increased by careful selection of crops for intercropping and relay cropping.

With only 500–600mm annual rainfall, only one crop is possible. However, intercropping is possible where there is 625–800mm of rain. Where rainfall exceeds 800 mm and water storage capacity exceeds 200 mm available water, sequential cropping of 2 crops is possible: rice - lentil on the Bihar Plateau, rice - chickpea in the Gangetic alluvial belt, and rice - horse gram on the subhumid red soils of Orissa, India.

FUTURE SOIL–WATER MANAGEMENT RESEARCH

Water is a limiting factor on rainfed land, and drought and flooding, which often occur in the same season, are a challenge to soil–water management specialists working in the rainfed rice–based cropping systems. Drainage of excess water, storage of rainwater for supplementary irrigation, soil–water conservation measures, desirable crops, and agronomic techniques to increase water use efficiency are some key measures to be exploited in rainfed Southeast Asia.

An analysis of long–term rainfall data should provide a region with predictions of the timing, extent, and frequency of drought and flooding. Crops and varieties that mature appropriately with the growing season need to be identified or developed for different agroclimatic regions, and runoff available for storage and irrigation should be determined.

Soil management for water conservation in different regions should be identified. Erosion control practices need to be identified and evaluated. Crop management practices such as time of sowing, seed placement, plant density, crop geometry, weed control, and efficient fertilizer use are important to maximize productivity per unit of water use. Intercropping, relay cropping, and sequential cropping with short turnaround times should be evaluated for maximizing water use and for providing stable food production.

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SUBSURFACE DRAINAGE OF LOWLAND RICE FIELDS IN CHINA

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Abstract

Characteristics of lowland rice fields and the use of sub–surface drainage for rice and upland crops are discussed, as is the effect of drainage on rice yields. Various subsurface drains, drainage configurations, and valves for regulating drainage are discussed. The paper includes a brief cost–benefit analysis of drainage systems.

SUBSURFACE DRAINAGE OF LOWLAND RICE FIELDS IN CHINA

Rice has been cultivated in China for nearly 7,000 yr and is the nation's main cereal crop. It is planted from the tropical island of Hainan in the south to temperate Heilongjing Province in the north and from Taiwan and the eastern coastal plains to the deserts of the west.

The main rice belt is south of the Qinling Mountains, along the Huai and Bailongjing Rivers. However, the rice area is expanding as new irrigation projects are completed, particularly in the North China Plain and Inner Mongolia. In Xinjiang and the northeastern provinces, rice is increasingly important. In 1982, 33.06 million ha of rice was planted on 29.1% of the cropped area in China, representing 45.6% of cropproduction.

The lowland rice areas are the Northeast Plain, the Two-lakePlain, along the middle and lower Yangtze River, the Pearl River Delta, and the western coast of Taiwan. More than 10 million ha of these areas suffer poor drainage and waterlogging. On these lands, water and aeration regime, inadequate or inappropriate fertilization, and low temperature can lower rice production. Additionally, wheat is planted after rice and its cultivation and growth requirements must be considered.

Subsurface drainage systems were developed for the rice-growingarea based on research conducted in the 1950s. Practical experience shows that subsurface drainage systems can effectively increase rice production.

CHARACTERISTICS OF LOWLAND RICE FIELDS AND THE EFFECT OF SUBSURFACE DRAINAGE

Much of the lowland rice is planted along rivers and lakes on poorly drained, low elevation or reclaimed land. Soil is lake and river sediment, field water level is high, and the cultivated soil layer is continuously saturated. The soil is sticky, heavy, and reduced with low cultivation potential. Fertilizer is not applied and productivity decreases over time.

At the China National Rice Research Institute (CNRRI) experiment station in Hangzhou, the soil is a fertile sedimentary clay (Table 1). The groundwater level fluctuates between 30 and 100 cm depth. Annual production is 8.2 to 9.0 t/ha.

Table 1. Properties of soils at the China National Rice Research Institute, Hangzhou, China.

Property	Depth	
	0-20 cm	20-38 cm
Organic matter content (%)	3.42	2.35
Total N (%)	0.233	0.154
Total K (%)	1.68	1.92
P_2O_5 (%)	0.103	0.183

In other areas, lowland rice is planted in eroding valleys and along creeks in mountains and hilly areas. Fields are frequently flooded by heavy runoff and cool spring water percolates through them. Natural drainage is low and groundwater level is high. Subsurface percolation and aeration ability are low, as are soil and water temperature. There are

high concentrations of organic acids, H_2S, Fe^{2+}, and Mn^{2+}, and pH is 5–6.

Subsurface drainage effectively removes excess ground- and soil-water. In early-seasonexperiments at CNRRI, subsurface drainage increased rice yield by 5 to 10%. Results in other parts of China indicated that subsurface drainage could increase yield by 5 to 15%. Following are the effects of subsurface drainage.

Controlling and reducing groundwater level

During rice growth, the groundwater table always is within 10 to 20 cm of the surface. In rainy season, it may be at the surface. With subsurface drains, the groundwater table can be lowered to 40 to 60 cm. Different rice growth stages require different groundwater levels. Data from Kwangtung Province (Table 2) indicate suitable groundwater levels for various crop stages, Groundwater level can be regulated by managing the drain gate.

Regulating percolation

Percolation rate at different growth stages influences water and nutrient supplies, aeration, and soil temperature. Experiments in different parts of China show that optimum

Table 2. Suitable groundwater depth for rice fields. Kwangtung Province, China.

Growth stage	Depth (m)
Between transplanting and tillering	0
Tillering	0.2-0.3
Sun-drying	0.5
Booting, shooting	0.3-0.4
Milk, maturity	0.4-0.5

percolation rate for rice is 8 to 10 mm/d at tillering, 15 to 20 mm during booting, and 10 mm at milk– and soft–dough stage.

An experiment at the Shanghai Academy of Agricultural Science showed that adequate percolation removes toxic and reduced substances from the root layer. Removal rate was 6.2 meq/100 g soil with percolation versus 0.62 meq/100 g soil without subsurface drainage, or 20% removal versus 6%. After 7 irrigations in early season, subsurface drainage increased oxygen reduction potential (Eh) by 30–100mV at 1 and 10 cm depth. With subsurface drains, it was possible to keep Eh above 100 mV at 10 cm depth, thus encouraging rice root growth.

Increasing sun–drying of the soil

Sun–drying the soil is important to rice field management, and can substantially increase grain yield.

After maximum tiller development, fields must be drained and sun–dried to limit growth of ineffective tillers and to strengthen rice stems. Sun–drying has the following advantages.

- It controls ineffective tillering, thus improving ventilation and sunlight penetration.
- It favors deep, strong roots, and increases white roots while reducing black roots (Table 3).
- It improves soil aeration and oxidation, thus removing toxic substances and encouraging organic matter decomposition (Table 4).
- It controls excessive stem and leaf growth, thus strengthening mature stems and preventing lodging.
- It increases differences between day and night plant temperature, and reduces relative humidity, thus decreasing disease incidence.

Table 3. Effects of sun-drying on the rice root system.

Sun-drying	Black roots (%)	Depth (cm) of root system
Yes	7.3	23-33
No	22.0	10-20

With subsurface drainage, fields dry in 3-5 sunny days. Without drainage it takes 7 – 8d.

Rapidly reducing the groundwater level

CNRRI experiments in 1984 showed that groundwater level in a field with subsurface drainage falls an average 4 – 1 mm/d, twice the rate of an undrained field. In undrained fields, irrigation must stop 7 – 10 d before harvest; in drained fields, 2 – 3 d before. With subsurface drainage, fields dry thoroughly and quickly for harvest, then can be planted immediately to wheat. Planting wheat in properly dried fields can increase yield by 15-20%.

KINDS OF SUBSURFACE DRAINS

There are two kinds of subsurface drains used in China: one with vertical ditches, called vertical drains, and one with buried pipes, called horizontal drains. Both are used to remove excess water and salt from the soil.

Table 4. Effects of sundrying on available N and phosphoric acid in soil.

Time	Available N (mg/100 g of soil)		Available phosphoric acid (mg/100 g of soil)	
	Light dry	Heavy dry	Light dry	Heavy dry
Before sun-drying	1.8	2.9	10.6	10.9
After sun-drying	2.7	3.1	10.7	15.9

Vertical drains

Vertical drains are most common in the large saline and alkaline lowlands of North China. Waterlogging and salinity and alkalinity are particularly serious in the diked, low-lying fields along the Yellow River. Rice is planted as a reclamation crop and irrigated with water from the river, which has a high silt content. From July to September, suspended solid content averages 24 to 29 kg/m^3. The sediment may contain as much as 0.8 to 1.5 kg N, 1.5 kg P, and 2 kg K; and organic matter is 0.9 - 1.0%.

Twenty years of experience show that reclaiming these lands through rice cropping requires vast amounts of irrigation water, which may raise the groundwater level and waterlog the soils. In these areas, vertical, gravity-flow drains have been augmented by tubewell pumped drainage.

In the Yellow River irrigation district, one, 35- to 40-m deep, 1-m-diameter vertical well is drilled for each 5.5 to 7.5 ha of riceland. Irrigation water is pumped from these wells to supplement that diverted from the river, and at the same time reduces the groundwater level.

The supplemental well water, delivered through a series of canals, serves specific crop needs at specific times. For example, seedlings are irrigated from the wells to keep the groundwater level 1.8 m below the surface and prevent salting. When fields are flooded with river water for transplanting, nutrient-rich silt settles on the soil. In the middle of the cropping season, fields are irrigated with river water and more silt is deposited. Later in the season, fields are irrigated with well water, which guarantees high rice yield and lowers the groundwater table for planting the following wheat crop. With a combination of gravity and pump irrigation, groundwater and salinity can be controlled and rice will yield more than 4.5 t/ha.

The 51.5 ha cultivated area of Xial Zhao Village in Yuan Yang County of Honan Province is a good example of this well irrigation system. The land is just beyond the Yellow River dike. It is low, waterlogged, and the groundwater level is 0.3 to 0.5 m deep. In 1970 vertical tubewells were drilled. The groundwater level has dropped to 2.5 m and salinity has declined from between 0.3 and 0.7% to 0.074% in the tilled layer. In 1976, combined rice and wheat yield was 5.3 t/ha – 4 times that in 1967.

Horizontal drains

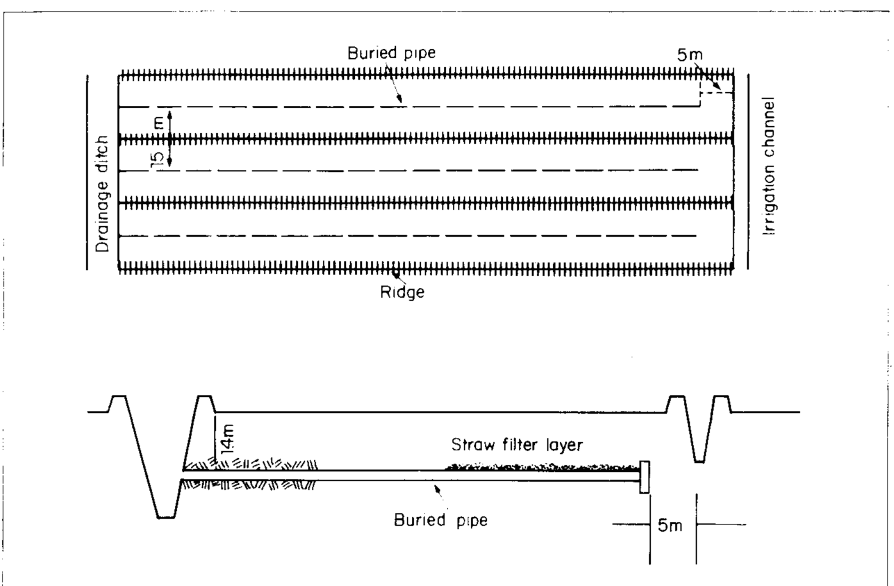
Buried pipe drains are used primarily in the lowlands of southern China, where most irrigation projects date from the

1950s. Planting rice in heavily irrigated fields for many years has raised the groundwater level. Now, especially in wet years, the high groundwater level decreases rice yield and adversely affects the following wheat crop. Subsurface drainage has become increasingly important.

Planning a horizontal subsurface drainage system. A horizontal subsurface drainage system is composed of drainage pipes and collecting pipes. Drainage pipes are buried in the last row of a field. They drain the water directly from the field and regulate groundwater level. Drainage pipes empty into buried collecting pipes that feed into large open drain ditches. Drainage and collecting pipes usually are buried in a single layer at the same depth. However, in clay soils with low permeability, or in soils with an impervious upper layer, two layers of buried pipes have been used.

Drainage pipes can be ceramic, concrete, asbestos cement, or plastic. Water enters through the joints and some pipes are perforated. Instead of tiles, earthen ditches, mole drains, and earthen ditches filled with filter material also have been used.

Figure 1 shows how drainage pipes are installed to collect field water and empty it into open ditches. Drainage pipes begin 5 or 6 m from the irrigation ditch to prevent



1. Buried pipe.

irrigation water from percolating into them, and the upper end always is closed to keep the drains from silting up. The 4 or 5 sections of pipe near the drainage outlet also must be sealed. These joints are filled with plaster or cohesive clay or lime so they will not leak. There is a valve at the outlet that controls drainage flow.

For field-drain installations, spacing must be closer if drain depth is shallower to provide the same degree of drainage. Rice roots grow 50 to 60 cm deep; therefore, drains should be 70 to 90 cm deep. If wheat, which has deeper roots, is grown, drains must be 100 to 120 cm deep. Deeper installation also protects tiles from heavy surface loads during tillage and harvest, prevents tile movement, and in northern China prevents freezing.

Proper depth of installation also is determined by soil permeability, depth to the impermeable subsoil, and the equipment available for installation. Appropriate installation depth varies considerably in different soils (Table 5).

In manual installation of buried pipes, drain lines are first plotted, then an open ditch is dug, with top width about 0.4 m, bottom width 0.1-0.2 m, depth 1.2-1.4 m, and grade about 0.1-0.2%. The ditch bottom is smoothed gently, and individual pipes laid (pipe length 0.3-0.5 m, inner diameter 8 cm, outer diameter 10-12 cm). The gap between successive pipes is 3 mm, except in sandy soils, where the gap should be as small as possible to prevent inflow of fine sand particles.

The top and sides of the pipes are covered by a layer of dry straw or rice husks as a filter. The dug-out earth is crushed and backfilled. All earth should be replaced or heaped over the trench so that after settlement the trench can be crossed with tillage equipment.

TYPES AND CONSTRUCTION OF SUBSURFACE PIPELESS DRAINS

In China there are various types of subsurface, covered, pipeless drains.

Backfilled pipeless drains

After rice harvest, while soil is still wet, trenches 0.2 m wide and 0.2 m deep are dug by spade at 4-8m spacing parallel to the line of crop tillage. The excavated soil is placed as small embankments along the trench sides. The trench bottom is smoothed, and a 6-cm-wide channel excavated to 60-cm depth along the middle of the trench (Fig. 2). The

Table 5. Spacing and depth of installation of horizontal drains on different soils.

Soil	Spacing (m)	Depth (m)
Clay	8-12	1.0-1.2
Loam	15-17	1.0-1.2
Sandy loam	20	10

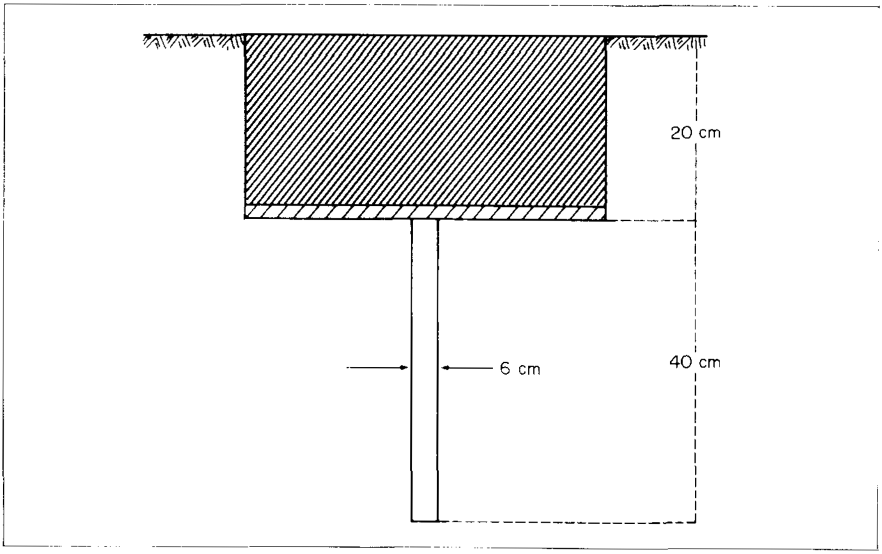
bottom of the main trench is then covered with 20-cm-wide, straw-reinforced clay bricks, and the trench backfilled with loose earth gently compacted. Such drains have a life of 1 or 2 yr.

Backfilled pipeless drains with filters

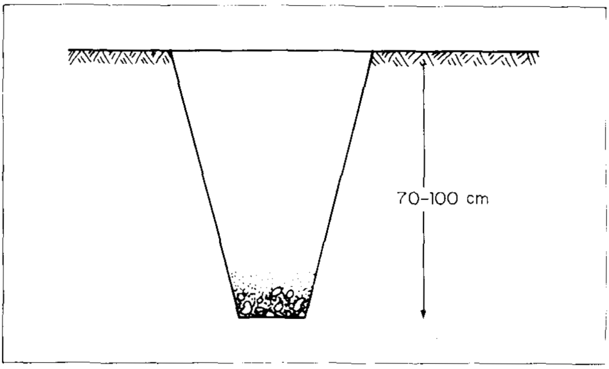
A tapered trench (Fig. 3), with bottom-width 0.2-0.3m and depth 0.7-1.0m, is backfilled with sand, gravel, and soil.

Mole (rat hole) drain

A mole plow (in China, a rat-hole cutter), pulled by a tractor, cuts a mole channel (rat hole) parallel to the field



2. Earth ditch.



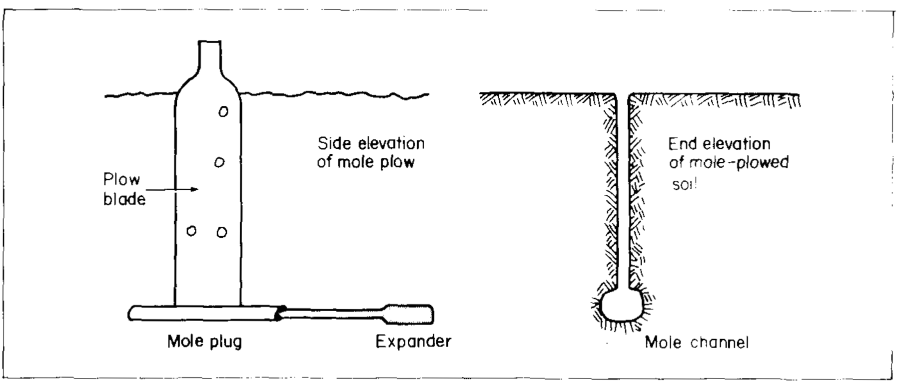
3. Earth ditch with filter.

surface (Fig. 4). Channels are spaced 2–4 m apart, and their outlets are connected to more permanent ditches or pipe drains. Mole channels are best created just after rice harvest when topsoil is dry enough to support tractor weight and give traction and the subsoil sufficiently wet and plastic to produce a smooth channel behind the mole plug and expander. In such conditions, mole channels can be created at 0.6–0.9 m depth using draft power of 20–50 kW. In drier conditions, power requirement is higher, soil fracture takes place, and stable channels are not formed.

Mole channels can be used for rice and wheat. They can persist usefully for 2–5 yr in heavy clay soil, but readily block and collapse on silt or sandy soils.

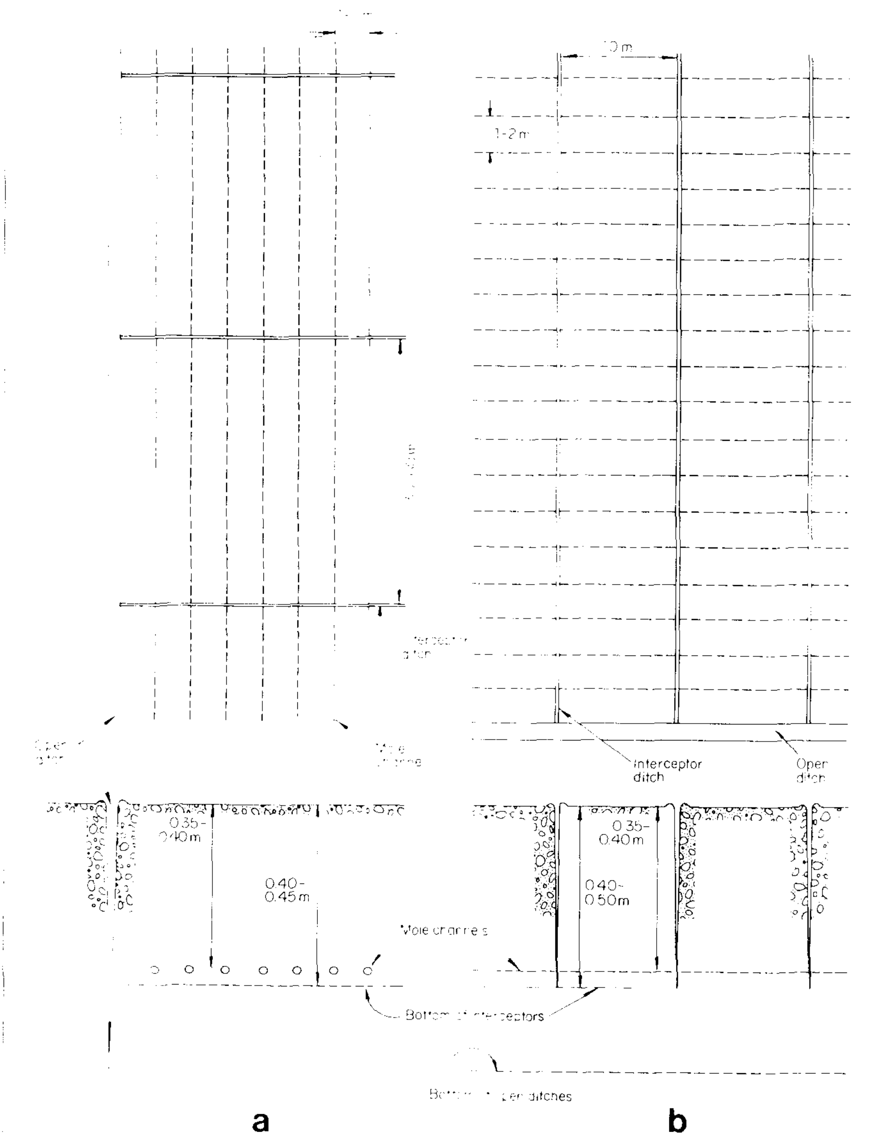
Shallow mole drains

Mole channels are at 0.35–0.40 m depth and 1–2 m spacing. They are intercepted at right angles by narrow ditches that



4. Mole drain.

collect both mole and surface drainage and feed into a wider and deeper open ditch. The depth and spacing of the ditches depend on whether the mole channels are parallel to or perpendicular to the length of the field. For moles parallel to the length (Fig. 5a), ditches are 0.40- to 0.45 m deep at



5. Configuration of shallow mole drains.

30– to 60–m spacing. For moles perpendicular to the length (Fig. 5b), ditches are 0.40– to 0.50-m deep at about 10-m spacing.

Medium and deep mole drains

Mole channels are at 0.6 m depth, and the interceptor ditch is about 0.7 m deep. A simple regulating valve is fitted to the outlet of each mole channel. Such drains are efficient in lowering and controlling water table depth.

Narrow subsoil drains

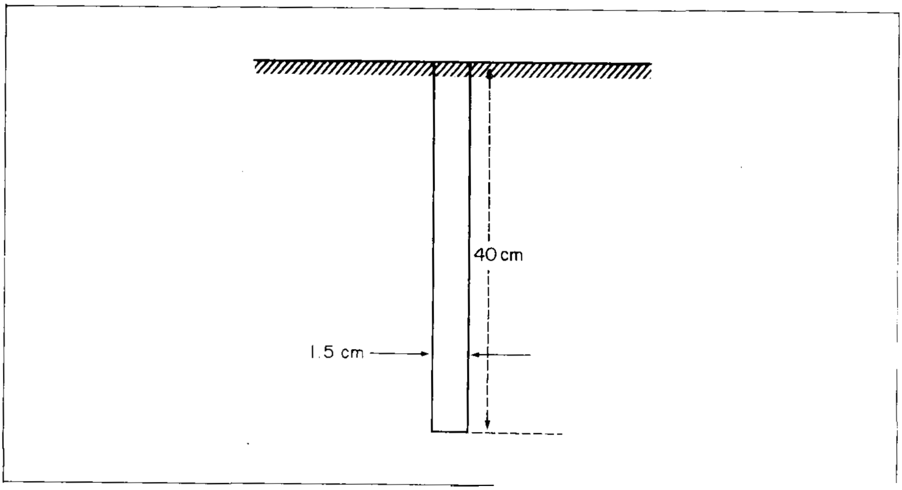
In soils with impervious plowpan layers, drainage can be improved through subsoil loosening and pan disruption by a trenching plow (Fig. 6). Soil disruption is to 0.3–0.4 m depth at lateral spacing of 0.3–0.8m. Cutting of the soil is accomplished by a rotating disc. Power requirement is of the order 40 kW -– similar to that required to create a subsoil mole channel that achieves comparable drainage. In field experiments of the Shanghai Academy of Agricultural Science, narrow subsoil drains reduced soil–watercontent in the 0–20 and 20–30 cm layers by 6 and 10%, and increased rice or wheat yield by 0.4 t/ha.

Combination drainage systems

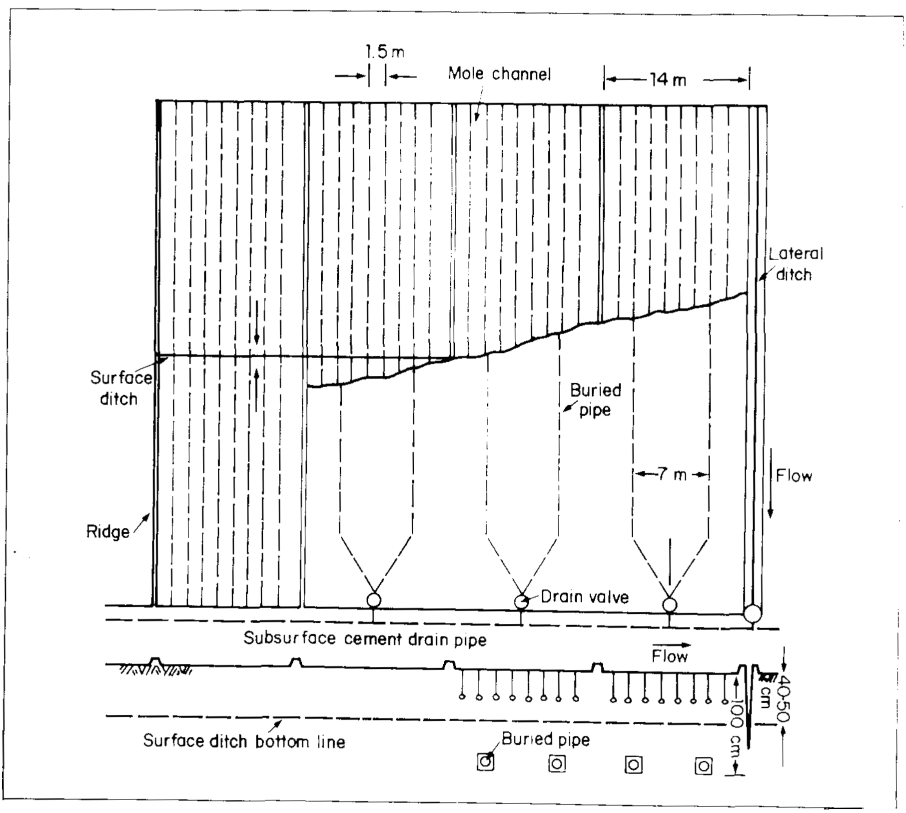
Mole drains may be installed in combination with, and over–lying, a deeper array of pipe drains (Fig. 7). The mole channels usually are at 0.5–0.6m depth, and the pipe drains at 0.8–1.0m. The two sets of drains may either be mutually perpendicular or parallel. The combination system removed 40–60% more water than the pipe drains alone -- with mole drains constituting 20–40% of the removal. When rice fields were sun–dried thoroughly at maximum tillering, drainage rate of combination drains was 1.0-1.8 mm/d higher than for pipe drains alone. Rice yields from early and late plantings correspondingly rose by 11.6 and 6.5%.

REGULATION OF RICE FIELD DRAINAGE

Effective regulation of rice field water level and of sub–surface drainage can help increase rice yields. By such



6. Narrow drainage trench.

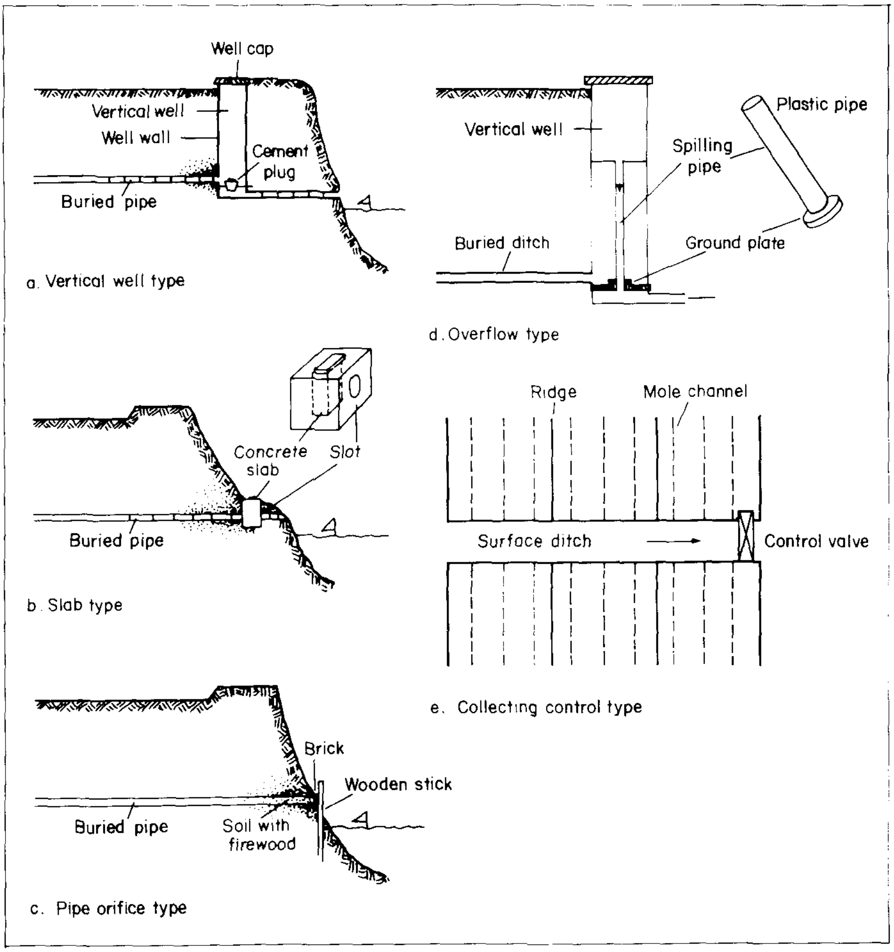


7. Double-layer drainage.

regulation, fields can be kept flooded when necessary, aeration and temperature regimes can be manipulated by adjusting percolation rates, and soil-drying at midseason draining and at rice harvest and wheat planting can be expedited. There are five or more types of regulatory valves currently used in China (Fig. 8).

Vertical well valve

The vertical well valve comprises a precast concrete pipe or a lime-soil wall. The valve at the bottom of the pipe is a simple cement stopper (Fig. 8a). This regulatory system is



8. Subsurface drainage control.

suitable for mole drains and for steep and slight field slopes.

Slotting slab valve

In the slotting slab valve, valve action is provided by a concrete slab that slots with a matching block (Fig. 8b). It is suitable for shallow slopes and is inexpensive and easy to use, provided that the slab fits tightly but smoothly into its block.

Orifice valve

The orifice valve is constructed of short pipes connected by sticky clay to each other and to the drain pipe (Fig. 8c). The open pipe end has a plug of clay and straw and is closed by a brick held in place by a wooden stake. This design works reliably on shallow slopes.

Overflow valve

An overflow pipe is incorporated in a vertical well (Fig. 8d); setting of the overflow level, determined by groundwater height, is usually just below soil-surface level. Drainage is automatic when groundwater rises above the overflow level.

Control ditch

Subsurface drainage is controlled by an open ditch. Mole channels connect directly to each side of the ditch, at the end of which is a gate valve (Fig. 8e). The system is inexpensive but requires that fields be small and level. Total area should not exceed 10-15ha.

ECONOMICS OF SUBSURFACE DRAINAGE

Twenty years of subsurface drainage of rice fields in China have shown benefits of improved soil aeration and of opportunities for mechanization. Economic benefits of subsurface drainage by plastic pipes have been assessed from experiments on the Pearl River Delta in Kwangtung Province. Subsurface drainage with drain spacings of 10, 15, and 20 m gave rice grain yield increases of 1.6, 1.2, and 0.8 t/ha, respectively. The costs of drain purchase and installation (respectively US $549, $403, and $306/ha at the 3 drain spacings) could be recovered within 3–5 yr. For concrete or ceramic pipes at drain spacings of 10–20 m, costs were $4-$44/ha recoverable within 10 yr.

Mole drainage in the lower area of Zhangshow County of Kiangsu Province increased wheat and rice yields by 0.4 and 0.7 t/ha. Costs for ceramic pipes at 7 and 16 m spacing were $219 and $104/ha, and for earthenware pipes at 10 and 20 m spacing were $115 and $58. Both systems would repay their outlay within 1–2 yr. For plastic pipes at 10 m and 15 m, repayment would require 2–4 yr.

The combination system of medium and deep mole drains has been adopted by farmers in Kia–sing County of Zhejiang Province. Costs are $48 or $63/ha when 7 or 8 persons undertake the mole operations. Wheat and rice production rose by 20–40% and by 10%, giving a refund of investment within 2 yr.

PHYSICAL ASPECTS OF THE ROOT AND SEED ENVIRONMENT IN LOWLAND SOILS

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ABSTRACT

Lowland soils differ in pore size distribution and moisture status from upland soils of similar texture. Pore size and moisture status strongly influence other physical properties of the soil that affect plant growth. A predominance of small pores increases moisture retention, decreases aeration, alters heat relations, and causes a rigid soil structure.

Favorable temperature and good seed–soil contact to ensure adequate water supply are necessary for germination. Proper aeration and low soil strength are necessary for seedling emergence. Root growth and function also require suitable regimes of air, water, and temperature. If root growth is efficacious, so also may be aboveground plant growth and yield.

In rice–based cropping systems, the successive crops may require differing soil physical environments, and soils must be managed accordingly.

PHYSICAL ASPECTS OF THE ROOT AND SEED ENVIRONMENT IN LOWLAND SOILS

Plants grow in two different environments. Leaves and stems grow in sunlight and air. Roots grow beneath the soil, from which they abstract water, nutrients, and oxygen. The two environments interact at the soil–atmosphere interface, but retain their individual characteristics.

Shoots grow in a gaseous atmosphere of almost constant composition, but drastic changes occur in the soil atmosphere under cropped soils. Conversely, roots experience only small changes in relative humidity and temperature, but shoot environments vary diurnally and seasonally. The soil environment must favor seed germination, seedling emergence, optimum root system development and function, and water and nutrient transport and storage. Moreover, optimal root environments and their physical and chemical characteristics may be crop-specific.

PHYSICAL ASPECTS OF LOWLAND SOILS

The nature and size distribution of mineral particles are the only stable soil characters. Organic matter and biological life vary with the environment. Soils inherit most of their physical properties from the arrangement of primary and secondary particles constituting the soil fabric. The particles pack together, leaving small open spaces that form a system of different sized pores that permeate the soil. If soil particles were uniform and spherical, the tightest packing would have 20% porosity. With particles in cubic packing, very high porosity is possible. Loosely packed, well aggregated soils may be twice as porous as densely packed, disaggregated soils.

Pore size distribution is more important to plant growth than total porosity. Pore size distributions for some undisturbed samples of Punjab soils, calculated from Sur and Singh (26), reflect the influence of texture and management (Table 1). In dunal Bhanra coarse sand, most pores are larger than 30 mm diameter. For the finer–textured soils much more of the porosity is contributed by the smaller pores. Samana and Fatehpur soils are fine sand, but lowland Samana soil has a larger proportion of small pores than the Fatehpur interdunal upland soil.

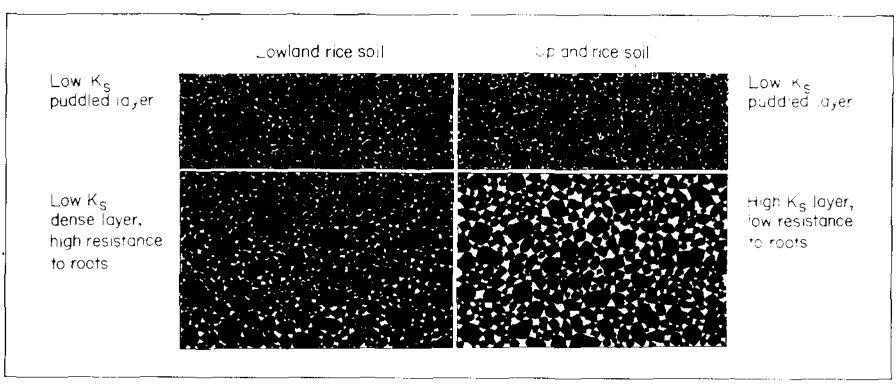
Changing a pore size distribution alters soil strength and soil–root contact dynamics, and changes soil–heat, soil–water, and soil–air relations, all of which strongly influence plant growth.

Table 1. Pore size distribution from undisturbed samples of surface horizons of some Punjab soils.

Poresize (µm equivalent sphericaldiameter)	Percentage fraction of total pore space				
	Bhanra coarse sand	Fatehpur fine sand	Samana fine sand	Tulewal sandy loam	Chatehra silt loam
>30	90.1	78.8	58.6	14.2	2.4
9-30	1.6	8.9	11.6	7.6	14.7
3-9	3.0	2.6	10.0	28.7	35.8
1-3	1.0	2.3	4.6	9.9	15.8
0.6-1.0	0.6	1.9	2.0	3.6	2.8
0.2-0.6	0.5	1.8	1.0	14.4	0.8

A soil's shear strength is a manifestation of inter-particle bonding and of the shape, size, spatial arrangement and orientation of soil particles, which affect the particles' resistance to displacement. Seed germination and root extension both require particle displacement, which only can happen when particles move past each other and there is pore space available to absorb the displaced particles.

The extent of particle interlocking depends upon soil texture and packing. The strength of interparticle bonds is a function of attractive forces, including cementation. Friction is determined by the shape, size, and orientation of particles to each other and to the angle of displacement. Lowland soils cropped in rice-based systems tend to be closely packed. A higher density layer usually develops below the plowing depth that restricts root penetration and reduces air and water movement. Upland soils may or may not have a layer of higher density (Fig. 1).



1. The high density layer below puddled surface soil.

Plowing wet soil increases bulk density and penetrometer resistance. A penetrometer measures resistance to compression, friction between soil and metal, and shear strength. Resistance to root penetration is rather different. Roots exert both axial and radial pressure, have less friction with soil particles, and bend to pass obstructions. Root diameter in annual plants ranges from 0.5 mm to 50 µm, with root hairs as thin as 10 µm. Roots therefore cannot penetrate rigid pores less than these sizes; nor can they penetrate systems with shear strength greater than 3 MPa. Shear strength of dry lowland soil may be greater.

Thermal properties of soils are related to soil composition and water content. In dense soils, more particle contacts increase thermal conductance. Soil water also increases conductance by acting as a bridge between particles. Soil air is a very poor heat conductor. At very low water content, thermal conductivity may be less than 0.5 W $m^{-1}K^{-1}$, because heat is transmitted through direct particle contact. But at saturation, thermal conductivity may range between 1.5 and 2.0 W $m^{-1}K^{-1}$

Baver et a1 (3) showed that thermal conductivities of dry soil increased by 30, 65, and 110% as soil bulk density increased from 1.1 to 1.2, 1.3, and 1.5 t/m^3. When soil moisture increased from 25 to 50% of soil saturation, conductivity increased severalfold. Thermal conductivity is greater in lowland soils than in upland soils with comparable texture because lowland soils are more densely packed and have higher moisture content.

Surface and subsurface soil temperature depend on the input and partitioning of net radiant energy, on thermal conductivity, and on heat capacity. Shortwave radiation absorbed at a surface is dissipated through various processes. Much of the absorbed energy may be used to evaporate water if the surface is wet soil or a dense crop cover. Part of the energy heats the soil and/or the crop tissues. The remainder is convected from the surface. For the bulk soil, heat capacity increases with water content.

The physical parameter that determines the time rate of change of temperature is thermal diffusivity, defined as thermal conductivity divided by volumetric heat capacity. Both these latter parameters change with water content in the same sense so that diffusivity and soil temperature are relatively less affected by changes in water content. Nonetheless, because of their much higher moisture content, lowland soils do have more stable temperatures than upland soils.

Both at the surface and in the bulk soil, temperature changes are roughly sinusoidal, with diurnal and annual periodicities. The amplitude of the temperature wave decreases with soil depth, and for diurnal variations has a magnitude at 0.3 m depth of about 1/25th of the surface amplitude.

Soil temperature affects seed germination, seedling emergence, root extension, water and gas fluxes, microbial activity, solubility and flux of nutrients and soil solutes, and other processes and interactions that influence plant growth.

Water relations of lowland soils under rice-based cropping systems often are determined by a pore system in which small pores predominate, and in which continuity of the larger pores is broken by compact subsurface layers. During puddling, lower layers are compressed and soil particles and inorganic and organic soil constituents form a denser subsurface soil structure. Moreover, when lowland soils are tilled for crops after rice, the subsurface soil moisture content may be appropriate for particle reorientation. Water retention and movement in lowland soils cropped with rice-based systems are influenced by this two-layer system (Fig.1).

In rice culture, required low water percolation is achieved through effective puddling of the surface soil. Conversely, for upland rice conditions and for nonrice crops following lowland rice, the subsurface layer and its pore size distribution have increased importance. A compact subsoil layer obstructs root penetration and prevents free surface drainage, thus increasing water retention in the surfacesoil.

In a compact subsoil layer with a few wide pores, root growth is less restricted and there may be less drainage and higher moisture retention as compared to a uniform soil of the same porosity but in which pores are continuous and of equal size.

Aeration, temperature regime, and soil strength all are affected by water content. These effects are not so important for lowland rice, but are important for crops grown after rice. High moisture content after irrigation or rainfall can cause oxygen stress in upland crops. Shallow rooting encouraged by dense subsurface layers often exposes crops to drought-induced moisture stress in lowland soils.

Soil air occupies pore space not occupied by moisture. Air content is determined by pore size distribution: lowland soils with many small pores have less air porosity than upland soils. The composition of soil air varies in time and space. Spatial variation is caused by differences in moisture, respiration, gas exchange rates, and pore continuity. Temporal variation results from temperature and moisture inhomogeneities that change the metabolic activity of the rhizosphere and the rate of gas exchange between soil and atmosphere. Under average conditions, carbon dioxide production in the root zone is 0.2–0.6 mg $m^{-3}s^{-1}$, which corresponds to oxygen consumption of 0.15-0.45 mg $m^{-3}s^{-1}$ for aerobic respiration. The relative contents of oxygen and carbon dioxide are determined by the rates of oxygen consumption and carbon dioxide production and by the rates of diffusion of the gases to and from the soil surface. (Mass flow of air contributes very little to the gas exchanges.)

In summer in temperate latitudes, oxygen flux into well-drained porous soils can be 0.01 $m^3d^{-1}m^{-2}$ land surface. Winter values are about 1/10th of this (5,8). In lowland soils, low cross-sectional area available for gas flow and low diffusion coefficient because some pores are water-filled, reduce gas fluxes. Results of Currie (6) and of earlier scientists show that coefficients for gaseous diffusion in soil have a roughly fourth-power dependence on air-filled porosity.

A high renewal rate of soil oxygen does not guarantee an adequate supply of oxygen to the roots. Water films between soil pores and root surfaces resist oxygen supply to roots because oxygen diffuses 10^4 times more slowly through water than air. When soil is water-saturated, the oxygen dissolved in soil water may be depleted in a few hours, causing anoxia.

Soil-seed and soil-root contacts are important during germination and seedling emergence, and in root growth. The processes that depend on these contacts are governed directly or indirectly by soil density, moisture, and temperature. Soil-seed contact depends on the seedbed and postseeding soil treatment. Loose soil-seed contact in a dry bed may lower germination. Seeds absorb water, swell, and push soil particles away, even in densely packed soils. Swelling pressures of 40 MPa have been reported for dry wheat and maize seeds. Pressures are less than 1.0 MPa at visible germination. Those pressures are larger than the 0.12 MPa reported for normal mechanical soil stress (11). Good seed-soil contact also is needed for anchorage as the radicle pushes its way through the soil. This factor also is important for emergence from otherwise loose seedbeds that develop thin surface crusts following a light rainfall after seeding.

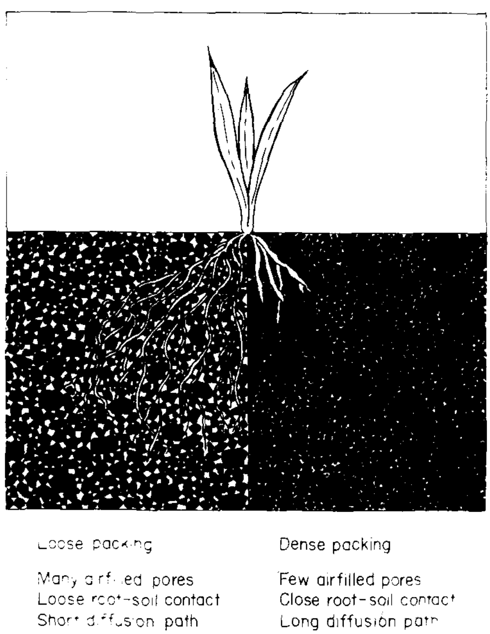
Root-soil contact anchors the seedling while roots exert pressure during extension. It determines the amount of root surface available for water and oxygen uptake. In closely packed soil where most of the root is in close contact with soil particles, the area available for gas exchange is limited (Fig. 2). Inadequate contact with a relatively dry soil may disconnect the absorbing roots from the water films that adhere to the soil particles. Often, in clay soils that crack extensively on drying, roots are left dangling in space.

THE SEED AND ROOT ENVIRONMENT IN LOWLAND SOILS

Seed germination

A seed must have favorable environmental conditions to germinate. Water transfer to the seed, gas exchange, and appropriate temperature are particularly important. Water absorption by dry seeds has three phases: imbibition, seed activation, and germination. In each phase the absorption process is controlled by seed-waterpotentials and seed diffusivities to water, soil-waterpotential, hydraulic conductivity of the soil surrounding the seed, and seed-soil-water interface hydraulic properties (11).

During imbibition, water enters the seed in response to differences in seed- and soil-water potential. Air-dried



2. Root-soil contact and aeration status in compacted soils.

seeds have extremely low (–50 to –100 MPa) water potential. With good soil contact, dry seed can absorb water from soils at wilting point (–1.5 MPa), but may germinate slowly. The number and area of soil–seed contacts increase as seed size increases relative to that of soil particles. At low moisture content, water enters seeds through these contact areas.

Water movement through the soil–seed system involves flux in the soil and into the seed, and water transfer within the seed. In studying these water transfers and their dependence on total soil–water potential, the osmotic and matric components of potential cannot be combined because membranes allow solute transport both into and out of the seed. Values for critical matric potential at the seed surface have been computed for maize, sorghum, clover, cotton, and chickpea, respectively, as –1.4, –2.0, –0.5, -1.1, and –1.5 MPa.

Seedbed characteristics are modified by tillage and compaction through effects on soil density and on transmission and concentration of water, oxygen, and heat. Temperature, oxygen, and carbon dioxide concentration affect respiration differently, depending upon the germination stage.

Oxygen uptake varies with species, cultivar, and germination stage. Wheat seeds cannot germinate without oxygen; rice seeds can, but their subsequent growth is abnormal. The coleoptile becomes unusually long and the first leaf and radicle and nodal roots may not grow at all (34). Kordan (14) studied coleoptile emergence of rice seedlings germinated under oxygen deficiency and found no visible evidence of primary root emergence. Atwell et al (1) reported that germination and early coleoptile growth in rice were inhibited by low oxygen concentration, but elongation was unaffected by low oxygen or anoxia. Some indicas need more oxygen than japonicas to germinate, root, and grow (19, 27). Thus, for rice in lowland soils, shoot projection and seedling establishment usually are less than optimal because of lack of oxygen.

Seeds have different temperature ranges for germination, Optimum temperature allows maximum germination in minimum time. High temperatures cause metabolic failure during germination and decrease emergence. Low temperatures slow or stop germination.

Optimum temperatures for germination and seedling emergence have been reported for various species. Singh and Dhaliwal (23) found that winter crops like wheat germinated in a wide temperature range. Rice germinates only between 10 and 40°C, and germinates best (34) between 20 and 35°C.

Probable percent emergence was more sensitive to temperature than final seedling emergence (23), but 30°C was optimum for both germination aspects. At 41°C. germination almost stops.

Root growth response to the soil physical environment

The soil physical environment influences root growth and function. Roots also influence the soil environment, but their effect may be overshadowed by those of water and temperature. As soon as the radicle emerges from the seed coat it must penetrate the soil, as must roots that develop and extend in different directions.

Primary roots grow down, elongating 1–20 mm/d. Secondary roots may grow horizontally for several cm before turning down. In the surface layer of well-structured upland soils, root concentrations may be 25–50 cm cm^{-3} (2). In dense lowland soils, root growth and function are restricted by low porosity and small pores, which affect the movement, content, and availability of heat, air, water, and nutrients. Growth also is restricted by high soil strength, particularly if the soil dries.

Compaction limits root growth because it reduces the large pores needed for root penetration. Pate1 and Singh (20) reported that compact, sandy soil reduced rice root growth but increased water use efficiency by lessening deep percolation losses (Table 2). Goss (9) demonstrated that roots cannot decrease their diameter to enter small pores. When roots encounter small pores, they must exert force to enlarge them.

Growth studies indicate that roots exert pressures of about 1 MPa and that maximum pressure usually correlates with the osmotic potential of root cells. In small, rigid pores, radial growth of roots increases from the base to the tip. Shierlaw and Alston (22) found rye and maize roots could not penetrate soil layers of bulk density greater than

Table 2. Effect of soil compaction on root growth and water use efficiency in rice.

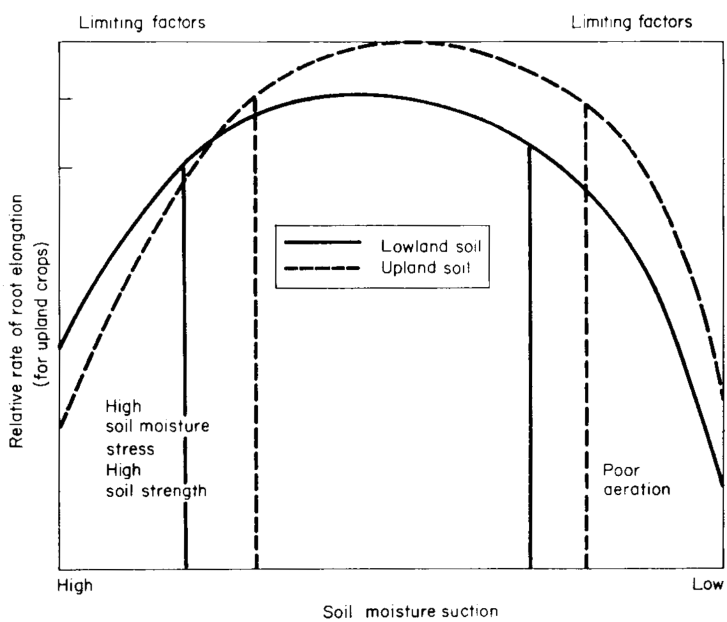
Soil bulk density (t m^{-3})	Root density (mg cm^{-3}) in depths (cm)				Water use efficiency (kg ha^{-1} cm^{-1})
	0-5	5-10	10-20	20-30	
1.66	9.0	1.8	0.4	0.2	26
1.75	1.1	1.4	0.3	0.1	32
Puddled	7.3	1.6	0.2	0.1	26

1.55 t/m^3. Taylor and Ratliff (28) showed that root growth rate decreased when penetrometer resistance increased beyond 0.5 MPa.

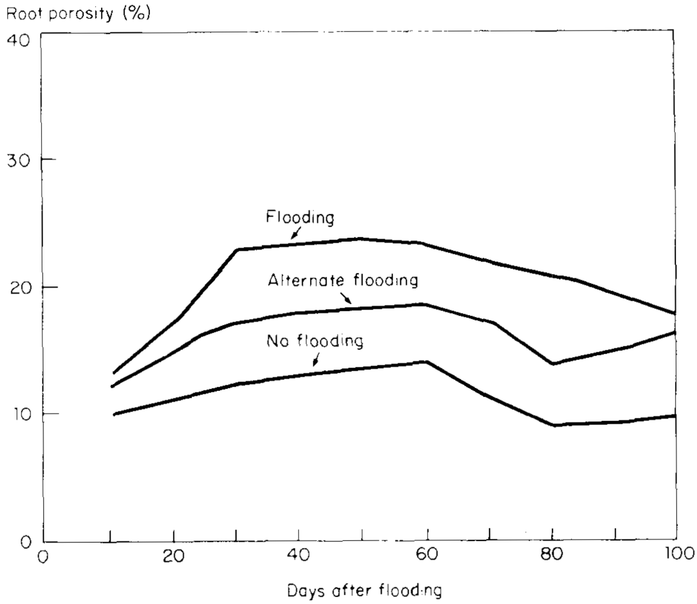
The effect of high soil density in raising mechanical resistance to root elongation may be compounded by hypoxia. Roots lose salts under anaerobiosis. Falling osmotic potential and loss of turgor may reduce the ability of roots to overcome soil resistance, Wiersum (32) emphasized the difficulty of ascertaining the importance of mechanical resistance in the field because its effect is similar to that of excess water and inadequate oxygen.

Figure 3 shows ranges of soil-water content in which high soil strength or poor aeration limits upland-croproot elongation rate in lowland and in upland soils. If adequate root elongation rate is defined as 90% or more of the maximum rate, then the optimal soil-water suction range for lowland soils begins and ends at levels higher than those in upland soils.

In lowland soils, elongation of rice roots is also affected by oxygen concentration. Oxygen supply to roots is by radial diffusion across the root surface and by internal transport from leaves and stems. Plants adapt metabolically,



3. Relationship between soil water suction and root elongation rate in upland and lowland soils.



4. Effect of flooding regime on aeration porosity in rice roots.

anatomically, and structurally to low oxygen conditions, and die only under complete root-zone anoxia. Das and Jat (8) found that aeration porosity in roots increased with flooding up to the most active rice growth stage (Fig. 4). However, root aerenchyma is not always associated with the ability to survive lowland conditions. Even rice roots are sensitive to anoxia (31).

Plants other than rice often experience in lowland soil hypoxia and, occasionally, conditions near anoxia. Stolzy and Letey (25) measured oxygen diffusion rate (ODR) using a platinum microelectrode. They found that ODR between 6 and 2 x 10^{-4} kg m^{-2} h^{-1} slowed or prevented cereal root growth. However, there are doubts about the validity of using oxygen electrodes in soil, where hydrogen dissociation likely augments the induced electrical current (16). Caution is therefore needed in relating root growth to ODR. It may be that flux density of oxygen flow to the root should more causally relate to root growth.

Blackwell and Wells (4) measured soil oxygen flux in winter oats and found that root extension rate did indeed correlate more strongly with flux than with ODR. Root extension stopped when the flux reached zero. Moreover, determinations of growth-limiting ODR may be affected by intensity of soil microbial activity. Field measurements (15, 29) show that carbon dioxide production, and oxygen consumption, by rhizosphere microorganisms may be as much as 1/3 the total of root plus soil microbial respiration.

Both root and microbial respiration increase with soil temperature. Therefore, oxygen available to roots can decline because of decreased oxygen supply or because temperature has increased respiration and oxygen demand. Sojka et a1 (24) studied the effect of oxygen and temperature on wheat roots (Table 3). Root mass increased with soil oxygen, but over the range 9–21°Cwas little affected by temperature.

There is nonetheless for each plant species a minimum soil temperature below which roots do not elongate (18). Walker (30) showed that above a minimum temperature of about 10 °C, maize–root elongation rate increased linearly with temperature to about 26°C and declined slightly between 26 and 32°C and rapidly above 32°C. Moorby and Nye (17) observed a curvilinear relationship between the elongation rate of rape roots and temperature, with a maximum at 23°C.

Low temperature may prevent development of rice radicles following germination (21). Yi and Chang (33) found root number and mass increased with temperature to an optimum at 27.5 to 29.9°C, depending upon the cultivar. Minimum temperature for root production was 14.2 to 17.8°C. Kar et al (13) reported an interactive effect of bulk density and submerged soil day/night temperature regime on root and shoot growth of rice grown in a sandy loam soil. The results (Table 4) show that root: shoot ratio increased with temperature but decreased with increasing bulk density. Bulk density had a strong effect on root growth when soil temperature was optimal.

Nutrient supply is much influenced by soil physical properties. The available pool of each nutrient is strongly influenced by temperature, soil–water content, and concen–

Table 3. Effect of soil temperature and oxygen concentration on root dry mass in wheat.

Temperature (°C)	Root dry mass (g plant^{-1})		
	Air (21% O_2)	O_2-depleted air (4% O_2)	N_2 (0% O_2)
21	0.70	0.47	0.21
15	0.84	0.65	0.09
9	0.76	0.55	0.19

Table 4. Interactive effect of bulk density and day/night soil temperatures on root and shoot growth in rice.

Bulk density ($t\ m^{-3}$)	Soil temperature regime (°C)			
	27/15	32/20	37/25	42/30
		Root-shoot ratio		
1.5	0.39	0.41	0.42	0.47
1.8	0.35	0.38	0.41	0.43
		Root dry mass (g $plant^{-1}$)		
1.5	1.5	3.1	3.5	1.2
1.8	1.6	1.8	1.9	1.5

trations of carbon dioxide and organic solvents. The availability of a nutrient to a particular plant is determined by the plant's rate of root extension, the diffusion coefficient of the mineral ion, and the uptake rate. The diffusivities of ions in soils are themselves influenced by porosity (bulk density), soil–water content, and temperature (Tables 5 [10] and 6 [12]). In the majority of cases the soil physical condition that will promote the best crop nutrition will also be that which supports the most extensive root growth (7).

CONCLUSIONS

In lowland soils, physical variables such as porosity and temperature can influence biological, physiological, and chemical processes in ways that have opposing effects on crop growth and yield. The soils must therefore be managed

Table 5. Self-diffusion coefficient of ions as affected by soil bulk density and temperature (10).

Bulk density ($t\ m^{-3}$)	Temperature (°C)	Diffusion coefficient of Rb ($cm^2\ s^{-1} \times 10^8$)
1.34	3.5	0.28
1.34	21.0	1.80
1.64	3.5	5.80
1.64	21.0	8.10

Table 6. Selfdiffusion coefficient of ions as affected by soil bulk density and water content (12).

Bulk density ($t\ m^{-3}$)	Gravimetric water content (%)	Diffusion coefficient H_2PO_4 ($cm^2\ s^{-1} \times 10^{10}$)
1.25	14	0.08
1.25	25	2.60
1.60	14	0.12
1.60	25	6.20

to create and conserve that physical environment that gives the maximum or the economically most favorable yield. It is the task of lowland-soil physical researchers to determine what is the desired physical environment; and anticipating that the optimal environment shall be site-specific, research must also determine how soil characterization and classification can help generalize these site-specific findings.

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ROOT BEHAVIOR : FIELD AND LABORATORY STUDIES FOR RICE AND NONRICE CROPS

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ABSTRACT

In submerged rice fields, measurements showed that the root system was nearly constant 30 d after transplanting and that, if soil mechanical impedance was not inhibitory, 90% of root length was in the 0 – 20cm soil layer at all growth stages. In a greenhouse experiment, withholding water for 16 d increased soil mechanical impedance at 0 – 20cm from 0 to 2.5 MPa. Rice root growth was 47% less than in a continuously flooded treatment. In a field experiment simulating rainfed lowland conditions, root growth decreased for soil mechanical impedance as low as 0.05 MPa. When soil mechanical impedance reached 0.3 – 0.5MPa, root growth and extension were 75% less than in a flooded control.

Soil mechanical impedance was measured in rice fields at 35 sites in South and Southeast Asia. The data suggest that except in the 0 – 10cm layer, mechanical impedance does inhibit root growth in flooded fields. Soybean roots did not penetrate subsoils of converted rice fields. However, if roots grow into the subsoil through cracks caused by drying, the soybeans can extract significant amounts of subsoil water.

ROOT BEHAVIOR: FIELD AND LABORATORY STUDIES FOR RICE AND NONRICE CROPS

Root growth of rice and upland crops is strongly affected by soil physical properties such as mechanical impedance, water content, texture, structure, and pore space. In submerged fields, rice root growth and yields also are affected by percolation rate.

Taylor (19) reviewed effects of mechanical impedance on root growth and emphasized the necessity of pertinent research in the tropics. Most studies on effects of soil physical properties on rice root growth have been small-scale (6, 11, 15, 18).

Development of traffic hardpans at various depths in lowland rice fields is well-documented. However, little is known about their effect on rice root growth. In rainfed and underirrigated lowland fields, rice roots often are inhibited by drought and increased mechanical impedance that is a function of soil bulk density and soil-watercontent. However, there is limited information on the effects of soil physical properties on root growth and yield of tropical irrigated and rainfed rice.

When clay soils dry, cracks often develop and extend to the subsoil. Thus, although drying can adversely affect root growth of upland crops after rice, because of high soil strength, the consequent cracking helps roots grow into the subsoil from where they may extract water.

RICE ROOT DEVELOPMENT IN LOWLAND FIELDS

Rice roots profusely and shallowly. Tables 1 and 2 summarize measurements of root and foliage growth for IR36 grown in a lowland field. The crop was seeded 17 Oct 1978 and transplanted 29 Oct at 20- x 20-cm spacing. Root and shoot sam-

Table 1. Growth behavior of IR36 grown in a lowland field.[a] IRRI, 1978.

	30 DT	42 DT	65 DT	92 DT
Plant height (cm)	64	81	102	105
Shoot mass density (g m^{-2})	206	465	747	1079
Root mass density (g m^{-2})	72.2	78.5	82.0	81.9
Root length density (km m^{-2})	17.7	17.5	16.5	14.7
Leaf area index	3.0	6.3	5.0	1.0
Root-shoot ratio (%)	35	17	11	8

[a] DT = days after transplanting.

Table 2. Vertical distribution of root density at different stages of growth for IR36 grown in a lowland field. IRRI, 1978.

Days after transplanting	Depth (cm) 0-5	5-10	10-15	15-20	20-25	25-30	30-40	40-50	50-60
	Root length density ($cm\ cm^{-3}$)								
30	22.7	7.9	1.8	0.9	0.7	0.5	0.3	0.1	–
42	22.2	6.4	2.3	1.6	1.0	0.7	0.2	0.2	–
65	21.6	5.0	1.6	1.2	1.1	1.2	0.4	0.2	–
92	19.0	4.7	1.5	1.0	0.9	0.8	0.5	0.2	–
	Root mass density ($x\ 10^{-4}\ g\ cm^{-3}$)								
30	11.85	1.79	0.64	0.13	0.09	0.05	0.03	0.01	–
42	13.00	1.42	0.51	0.35	0.21	0.11	0.04	0.02	–
65	13.46	1.54	0.49	0.30	0.24	0.19	0.07	0.03	–
92	13.01	1.56	0.66	0.37	0.34	0.27	0.07	0.07	–

ples were taken 30, 42 (panicle initiation), 65 (heading), and 92 (ripening) d after transplanting (DT). Root length was greatest at 30 DT, but plant height increased thereafter. Sixty-fiveand 90% of the root length were within the 0-5and 0-20cm soil layers, and 80% of the root mass was in the top 5 cm. Root:shoot ratio was 35% at 30 DT and decreased to 8% at maturity.

Soil mechanical impedance between 0 and 20 cm, measured by a cone penetrometer (of 30° cone angle, 3.23 cm^2 base area), was below that which impedes rice root penetration. We infer that the shallow root system is an inherent characteristic of IR36, and was not caused by mechanical impedance. There are reports that root mass and length are greater at heading (14) and that superficial roots, which develop after panicle initiation, elongate and branch until maturity (12). In our experiment, the root system was fully developed at 30 DT. Defining effective rooting depth as the depth above which root length density exceeds 0.5 cm cm^{-3}, the effective rooting depth of IR36 in this flooded soil was 30 cm. This is shallower than that of wheat, maize, and upland rice varieties but almost the same as for IR36 grown in upland fields (5, 21). Surface rice roots often break when soil cracks during midsummer draining in Japan. However, rice yield is not reduced, and appropriate water management after draining promotes high yields. Therefore, rice may have more than enough roots for water extraction in the thin surface soil.

In flooded, lowland fields, percolation and soil mechanical impedance are major determinants of root growth.

Root–boxexperiments showed that under submerged conditions, percolation favored deep root growth. Similarly, in a farmer's field where proximity to a deep drainage canal encouraged high percolation, deep rooting was observed (7).

Ishihara (9) found that percolation

- has limited effect on vegetative growth, but promotes nutrient uptake in the reproductive stage and increases percentage of ripened grains;
- promotes primary root elongation and the development of secondary roots and root hairs; and
- may eliminate from the soil toxic substances such as acetic acid.

The optimum percolation rate for root growth and yield is not known, but for yield to exceed 6 t/ha (hulled rice), percolation rate must be 15 to 25 mm/d (10, 9), and should never be less than 1 mm/d (20).

Percolation at late growth stages can be increased by intermittent irrigation, which also improves subsoil structure. However, high percolation can cause drought stress when irrigation water is insufficient, and will decrease yields if fertilizer is limited.

Kawada et a1 (12) studied the relation to hulled rice yield of root growth in the 0–5cm soil layer. For yields up to 6 t/ha (such high yields were achieved by N topdressing) they found strong correlation between root mass and grain yield. For yields higher than 6 t/ha, it was necessary to stimulate deep root growth by deep plowing and improved percolation.

EFFECT OF SOIL PHYSICAL PROPERTIES ON RICE ROOT GROWTH

Root growth after terminating irrigation

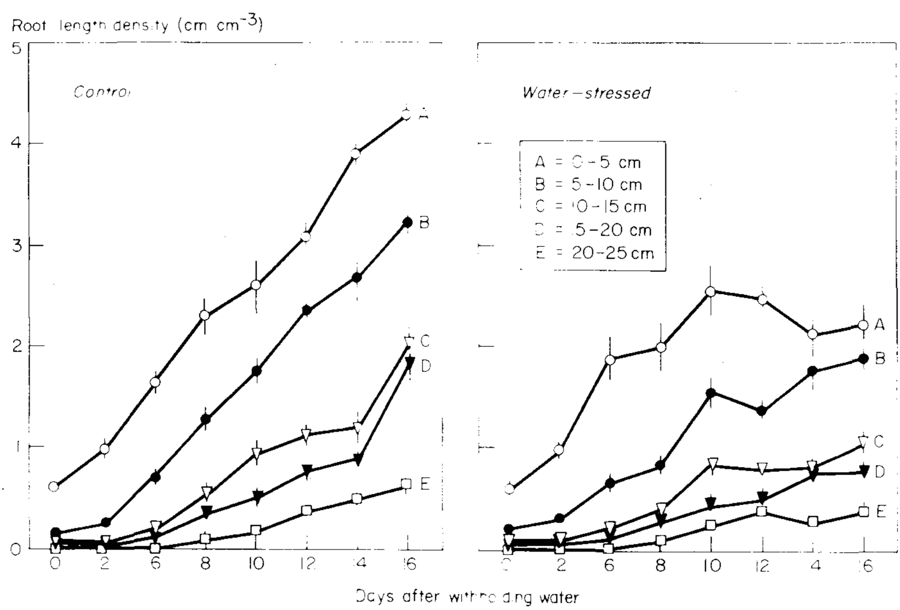
Soil physical properties affect rice growth in many ways. We concentrate on the primary physical factors and their interactions.

Rice fields develop traffic hardpans between 12 and 20 cm depth because of human, animal, and tractor compaction. Soil compaction increases bulk density and mechanical impedance to root growth. Little is known about the response of rice roots to increased bulk density (2, 17) and that information often is conflicting. In examining root response to soil physical properties, mechanical impedance measurements have been more useful than bulk density values (6,11).

In a 1983 greenhouse experiment in puddled soil we studied the response of IR36 roots to varying levels of drought that might occur in rainfed lowland rice culture. In a water-stress treatment, irrigation was stopped 17 DT. The control was continuously flooded with 2 cm of standing water. Soil and roots were sampled on alternate days over a 16-d drying cycle.

Dawn leaf water potential declined with soil moisture content. Soil moisture potential differed significantly between control and stress treatments after 6 d, and leaf water potentials differed significantly after 8 d. Water stress was maximum 16 d after stopping irrigation; dawn leaf water potential was then -1.0 MPa, and stressed plants showed severe wilting and rolled leaves.

There was strong interaction between root length density and soil and plant water status. Figure 1 shows changes in root length density of stressed and control plants with time and depth. When irrigation stopped, root length densities were similar in control and stressed treatments, and did not significantly differ until 10 d later. On day 12, however, root length density in the 0- to 10-cm layer differed significantly between treatments. Drought inhibited root growth in the 0- to 15-cm layer on day 14, and in the



1. Effect of water stress on root-length density of control and water-stressed treatments over time and at 5 soil depths. Data points are ± S. E. (Thangaraj and O'Toole, 1983, unpubl.)

0- to 20-cm layer on day 16. At 14 d, root length density in the stressed treatment was 37% less than in the control, and 47% less on day 16.

The significant decrease in root length density was associated with a progressive increase in soil mechanical impedance from 0 to 2.5 MPa in the 0-20 cm soil layer during the 16 stress days. Root length density at 20-25 cm did not differ between treatments. We assumed that the decreased root growth, especially in the upper soil layers, was partly a consequence of water stress-induced reduction of photosynthesis. Changes in soil physical structure must also have inhibited root growth. Soil mechanical impedance, averaged over the 0-25 cm soil profile, changed from 0.1 to 1.5 MPa, and root length density decreased 40%.

Despite this experiment, we still know little about changes in bulk density and mechanical impedance in lowland rice fields during a drying cycle (rainless period) or about how roots respond in situ to those changes.

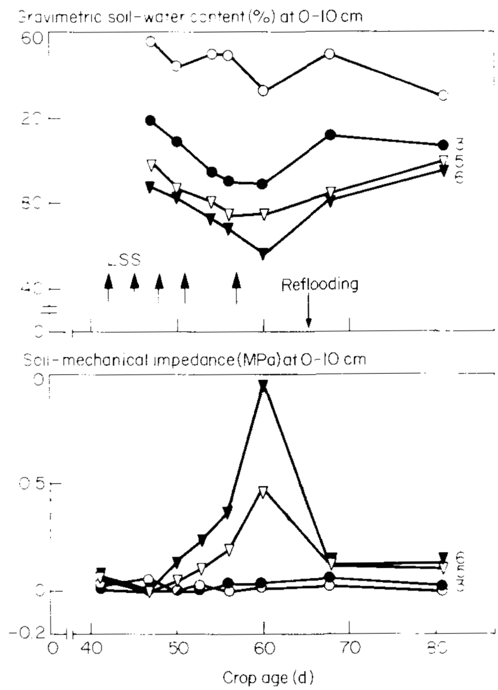
Although these laboratory and greenhouse studies showed similar trends, it was difficult to identify a threshold of mechanical impedance that inhibited root elongation or to establish a precise quantitative relation between treatment level and root growth. The experimental systems and methods, and the dynamic nature of root growth cause difficulties of measurement and interpretation. Some of these difficulties are specific to laboratory and greenhouse experiments and are mostly overcome in large-scale field experiments.

Rice root growth under drought and reflooding

We evaluated IR54 root growth in a 1984 field experiment that simulated rainfed lowland conditions. A line-source sprinkler irrigation system was used to create six water regimes. For four of them (1,3,5, and 6), root samples of 20- x 20- x 40-cm^3 were taken at 9 crop development stages. Three samplings were made during water stress, 42 to 61 d after sowing.

The results discussed here represent only the rice response during the irrigation treatment period and during 20 d after the field was reflooded. Data are presented (Fig. 2, 3) only for the upper 10 cm of soil, although samples were at 5-cm increments to 40 cm.

Soil mechanical impedance at 0-10 cm was closely related to soil-water content (Fig. 2). For regimes 1 and 3, penetration resistance was nearly constant. For regimes 5 and 6, soil mechanical impedance gradually increased until

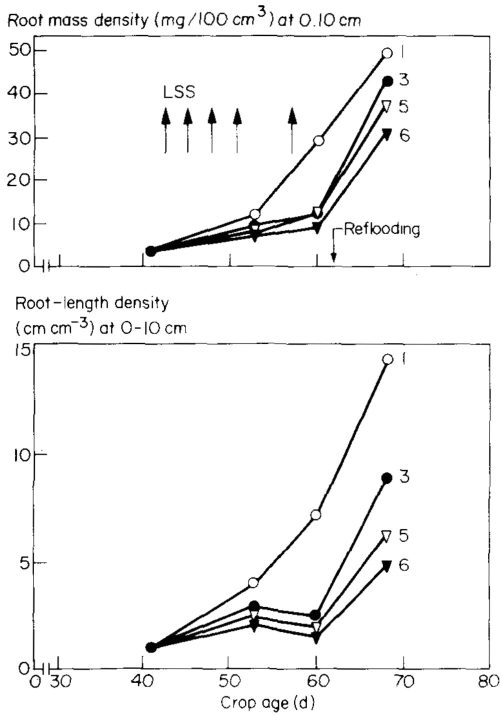


2. Effect on soil-water content and soil-mechanical impedance at 0-10 cm of 4 irrigation regimes between 42 and 61 d. Regime 1 was continuously flooded while regimes 3, 5, and 6 were drained on day 42, and until day 61 received decreasing amounts of water applied by a line source sprinkler (LSS) irrigation system (Thangaraj and O'Toole, 1984, unpubl.).

gravimetric moisture content had declined to about 70%, and increased considerably when soil-water content fell below 65%. Mechanical impedance for irrigation regimes 5 and 6 was reduced by reflooding, but not enough to equal the control levels, which were close to 0.

In the flooded treatment, root length density increased exponentially with time (Fig. 3). For regimes 3, 5, and 6, root length density at first increased, then decreased by the third sampling, when stress was maximum. The significant decrease for regimes 5 and 6 was thought to be caused by the death and decay of fine, fibrous roots in the upper layers of the drying profile. They died because of drought and high mechanical impedance. A similar decrease in root length density at regime 3, despite a very low mechanical impedance there, is presumed to have been caused by the moisture stress-induced death of fine roots.

Root mass density responded similarly to root length density in trend and timing (Fig. 3), but root length density decreased more than did root mass density. Root morphology also changed. This implies that roots became shorter and thicker in response to increased mechanical impedance, as has been previously observed (1, 3, 8); howev-

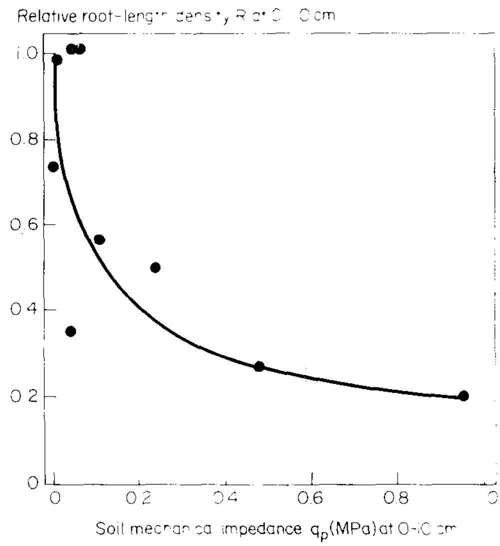


3. Response of root mass density and root-length density at 0-10 cm soil depth to 4 irrigation regimes between 42 and 61 d. Regime 1 was continuously flooded while regimes 3, 5, and 6 received decreasing amounts of water applied by a line source sprinkler (LSS) system (Thangaraj) and O'Toole, 1984, unpubl.).

er, the physical or physiological reasons for this thickening is unknown (4). Figures 2 and 3 suggest that root growth and extension were inhibited by decreased assimilate supply and increased mechanical impedance. The latter is a strong function of soil-water content and of shrinkage of the puddled Maahas clay soil. Thus the ability of the root system to actively expand and to abstract water was inhibited.

Reflooding the field reduced soil strength and increased root length density, but did not completely remedy the effects of water stress.

The finding that increased soil mechanical impedance decreased root length density is consistent with results from the greenhouse experiment. However, it appears that in the field, soil strength values as low as 0.05 MPa are sufficient to inhibit root growth (Fig. 4). Values greater than 0.3-0.5MPa decrease root growth and extension by 75%. Extrapolation of these results to other soils and water regimes is complicated by many site-specific soil physical properties, such as structure, texture, bulk density, and porosity.



4. Relation between root-length density relative to control R and soil mechanical impedance q_p in a drying puddled and lowland soil. The equation $R = (1.44^* 27.3\ q_p)^{-1/2}$ has a correlation coefficient of 0.95** (Thangaraj and O'Toole, 1984, unpubl.).

Soil mechanical impedance in rice fields

These initial studies illustrate the reaction of the rice root system to varying mechanical impedance. The implication of the studies for the major rice-growing regions can only be assured when the soil mechanical impedance characteristics are known for the rainfed and irrigated ricefields of more regions. In September and October 1983, therefore, soil mechanical impedance data were collected at 35 sites from experiment station and farmers' lowland rainfed rice fields in Burma, India, Nepal, Thailand, and the Philippines.

Measurements were made with a hand-held penetrometer of 60° cone angle, 6-mm-diameter base, and 0-35 cm depth range. Measurements were at various soil depths, either under standing water or in drained soil. Determination of soil-water content was impracticable, and information was unavailable on soil wetting and drying prior to measurement. Therefore, caution is advised in developing conclusions or extrapolations.

Nonetheless, a preliminary interpretation is possible. Data are separated as between fields with standing water and those without. In fields with standing water, mechanical impedance in the upper 0-10 cm cultivated layer averaged 0.64 MPa. Lower soil zones all had strengths >2.8 MPa: high enough to inhibit root elongation. In lowland, puddled fields without standing water, the 0-10 cm zone had a mean impedance of 1.7 MPa, and very high impedance levels in the lower zones. There were hardpans at several sites. At other locations, penetration resistance increased steadily with depth.

These limitations to root system development can cause many different crop responses. For rainfed rice, the active root zone appears to be only 10–15cm deep, and represents a soil–water reserve that during rainless periods would quickly be exhausted. One may therefore recommend that rice varieties might be selected or bred to have root systems that are vertically oriented and able to penetrate hardpans (11). Another solution is to break the hardpan by tillage. These problems and the possible remedies need much more research.

WATER EXTRACTION BY ROOTS GROWING THROUGH SOIL CRACKS

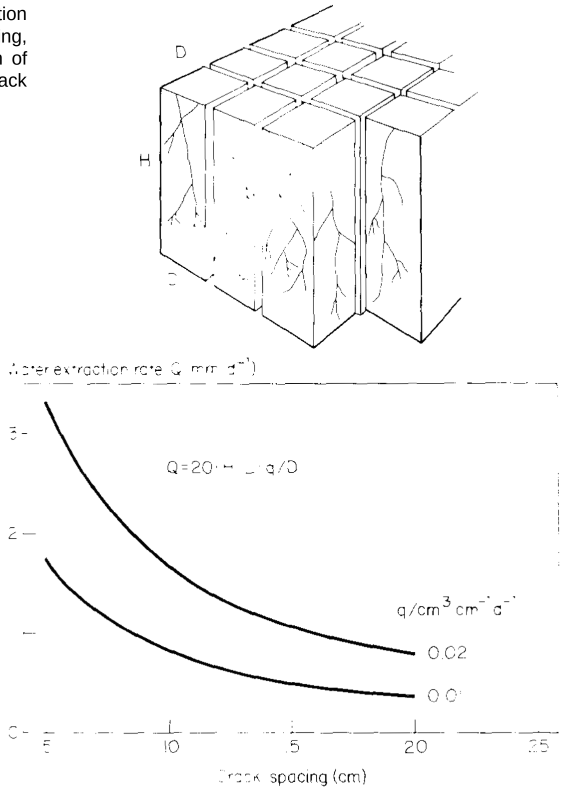
When puddled lowland rice fields are converted to upland crop cultivation, the soils (especially clays) usually are poorly drained; have a thin, plowed layer with a hardpan; and have insufficient subsoil air porosity for root growth of upland crops. As a result, upland crops are subject both to excess soil water and drought. When the subsoil dries and shrinks, roots grow down through the cracks. The cracks (whether natural or man–made) are important for subsurface drainage, but their effect on water extraction by roots is not well documented.

A lysimeter experiment at Tsukuba, Japan, estimated the amount of water extracted by soybean roots growing down soil cracks (16). The lysimeter plot (30–x 70–mx 0.65–mdeep) was a rice field until 1979, when it was converted to an upland field. The soil was more than 50% clay. Drainage was improved by installing a pipe drain with connecting mole drains. Converting from puddled soil to upland changed the structure of the surface 12 cm of soil from massive to aggregated, but did not affect the subsoil.

Two months after seeding, soybean roots had not penetrated the bulk subsoil, but had grown into subsoil cracks and fissures. Walls of cracks that had roots were sectioned into 10–x 10–cm grids, and roots in each grid were collected and measured. Root length densities were from 0 to 2.74 and averaged 0.92 cm cm^{-2} of cracked wall.

Water extraction by these crack–exploiting roots is difficult to measure. We therefore estimated water extraction using the model illustrated in Figure 5. Water extraction per unit ground area Q (mm/d) is given as:

$$Q = 20\ HLq/D$$



5. Relation between water extraction rate per unit ground area, crack spacing, and water uptake rate per unit length of root, as derived from a simple crack model.

where H is depth of cracks (cm), L is root density in the cracks (cm cm^{-2}), q is water uptake rate by unit length of root surrounded by soil particles (cm^3 cm^{-1} d^{-1}), and D is crack spacing (cm). The relation of water extraction rate and crack spacing was obtained by substituting the measures for H (45 cm) and L (0.92 cm cm^{-2} of crack) in the equation. Water uptake was from a root plane experiment (Hasegawa and Sato, unpubl.), and taken as 0.01 and 0.02 cm^3 cm^{-1} d^{-1}. Figure 5 shows that for cracks at 10–15cm spacing, and for uptake per unit length of root of 0.01–0.02 cm^3 cm^{-1} d^{-1}, then water extraction rate per unit ground area is 0.6 to 1.7 mm d^{-1}.

These values may be compared with upward fluxes of soil–water that may be calculated from the measured subsoil hydraulic conductivities and from hydraulic gradients obtained by tensiometers at 40- and 60-cm depth. These flux densities were only 0.01 mm/d for most prevailing soil-water conditions. Moreover, daily evapotranspiration of soybean in central Japan is typically 3.5 mm/d. Consequently, water extraction by roots in cracks might be important to water-stressed plants.

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WATER USE AND WATER USE EFFICIENCY UNDER DIFFERENT MANAGEMENT SYSTEMS FOR UPLAND CROPS

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Abstract

Water-balance experiments are described in which the internal drainage method was used to determine accurate values of unsaturated hydraulic conductivity and the zero flux plane method to determine soil-water flux. The experiments also investigated the effect of mulching on water use, water-use efficiency, and yield for various annual crops.

The measurements of water use showed that for Malaysian conditions the corrected Penman Method was the most suitable of several possible methods for predicting crop water use from meteorological data. For maize, mungbean, cowpea, chili, and grass, seasonal average water use was respectively 3.0, 3.6, 3.0, 4.0, and 4.2 mm/d.

Mulch at 3 t/ha improved yield of all crops tested, and increased water-use efficiency by as much as 90%. It reduced soil temperature at 5 cm depth by 5-10K.

WATER USE AND WATER USE EFFICIENCY UNDER DIFFERENT MANAGEMENT SYSTEMS FOR UPLAND CROPS

Malaysia has high annual rainfall, relative humidity, actu-a1:potential sunshine, and uniform air temperature. However, the large rainfall variability and the consequent floods and droughts determine the cropping patterns. Where there is no irrigation, uneven rainfall is a major constraint to productivity, both of rice and annual crops (3). Drought is frequent in Malaysia (ll), but water balances based on long-term averages fail to adequately show the effect of short-term rainfall variability.

Baillie (2) found that moisture stress is likely in most years in shallow Malaysian soils, and that stress lasting 10-12d can occur several times a year. Malik and Foster (10) reported that lack of soil water restricts yields of grain legumes in most of peninsular Malaysia.

Traditional crop water studies use water balances based mainly on weather data, assume no water movement within and between soil and subsoil layers, and predict soil hydraulic conductivity as an exponential function of soil-watercontent. Because this function is exponential, the predictions of hydraulic conductivity or of soil water flux can be grossly in error.

A more reliable method for determining water balances allows for vertical movement of water in the soil profile, and uses accurate field measurements of unsaturated hydraulic conductivity. These measurements are made by the internal drainage method using a neutron moderation soil-moisture meter and tensiometers to measure soil-water content and potential. This paper describes the determination of water use and the quantification of parameters in the water balance equation for annual crops in Malaysia.

MATERIALS AND METHODS

Field site and experimental layout

The experiment was conducted at Puchong Experimental Farm, Serdang, Selangor, Malaysia. The farm is on a clay soil of the Bungor series (kaolinitic, isohyperthermic, Typic Paleudult); surface soil is sandy clay loam, with a sandy clay subsoil. Slope varies from 0-10%,but is generally less than 5%. The top 1 m of soil is nonlateritic.

The site of the water balance study was free of laterite to 150 cm depth, was reasonably flat (slope 3-6%), and of tota1 area 73 x 20 m (about 1/7 ha). There were 16, 8- x 8-m plots with 1 m interrows arranged in 2 rows of 8. The lower row had a runoff collection system.

Each plot had 1 vertical, 2-m-long neutron moisture meter tube at its center, and tensiometers at soil depths of 10, 20, 30, 40, 50, 60, 80, 100, and 120 cm. Four plots had 2 sets of tensiometers at 10-cm intervals to 120-cm depth. Properly isolated, buried nylon tubing connected the tensiometers to a mercury manometer installed outside each plot.

Soil-water contents were determined using a Wallingford-type neutron moisture meter with a 50 mCi americium-beryllium fast neutron source, a boron-trifluoride slow neutron detector, and a rate meter.

Determining unsaturated hydraulic conductivity

Hydraulic conductivity in the field was determined using the internal drainage method (5), as described by Maesschalck et a1 (9). Hydraulic conductivity $K_{(\theta)}$ is calculated from

$$-\frac{\delta S}{\delta t} = q = -K_{(\theta)} \frac{dH}{dz} \qquad (1)$$

where S is storage per unit ground area, q is flux density, t is time and dH/dz is hydraulic gradient.

The water balance equation

The field water balance equation during time Δt of the soil underlying unit ground area can be written as

$$\Delta S = P + I - ET \text{ (or E)} - q_{z_r} - R \qquad (2)$$

where ΔS is the change in soil-water storage, P is precipitation, I is applied irrigation water, ET is actual evapotranspiration from cropped soil, E is actual evaporation from bare soil, q_{z_r} is the soil-water flux density at a depth z_r, and R is surface runoff. All variables except ET (or E) can be measured in the field. The main difficulty in solving the water balance equation is in estimating the soil-water flux component, which requires a precise knowledge of the profile of soil hydraulic properties.

Determining rainfall, changes in soil-water storage, runoff, and hydraulic head. Rainfall at the experiment site was measured daily using a gauge in the meteorological station just outside the field. Runoff was determined in 8 of the 16 plots from a 1.83- x 8-m area in each plot. Runoff was measured after each rain.

Volumetric soil water content was measured at depths of 10, 20, 30, 40, 50, 60, 80, 100, and 120 cm with a neutron moisture meter. Soil-water storage between depths z_1 and z_2 was calculated as

$$S = \int_{z_1}^{z_2} \theta \, dz \tag{3}$$

Changes in S between successive measurement times and for each soil layer were determined graphically. Tensiometer readings were taken simultaneously with soil-water content and at the same depths. Prom these readings, hydraulic head was calculated and plotted against soil depth. Hydraulic gradient (dH/dz), which determines the magnitude and indicates the direction of water movement, was then computed for the different depths and times.

Determining soil-water flux. A transitional zone can exist in the soil profile above which there is an upward soil-water flux (dH/dz > 0) and below which there is a downward flux or drainage (dH/dz < 0). The transitional zone is the zero flux plane ,(dH/dz = 0). Fluxes and water balances can always be calculated using Darcy's Equation (Eq. 1), but the existence of a zero flux plane may make it possible to calculate soil-water balances without Darcy's Equation.

In situations without and with a zero flux plane we may proceed as follows:

- Absence of a zero flux plane. Under these conditions, there is either continuous drainage or continuous upward movement, and flux density is determined by Darcy's Equation as

$$q_{z_r} = -K_{(\bar{\theta})} \frac{dH}{dz} \tag{4}$$

where $K_{(\bar{q})}$ is the hydraulic conductivity corresponding to an average soil-water content $\bar{q}$ during the period considered, and $(\overline{dH/dz})$ is the average hydraulic gradient during that period.

• Existence of a zero flux plane. The position of the zero flux plane can be determined from the hydraulic profiles measured by the tensiometers. The average depth of the zero flux plane Z_0 is taken as the arithmetic mean $\overline{Z_0}$ during a particular time period. Determination of ET by the zero flux plane method is possible only for uncropped soil or cropped soil where the rooting depth does not exceed $\overline{Z_0}$ In other cases, Eq. 4 must be used to determine the flux and ET or E. In the first two cases, ET can be calculated from Eqs. 2 and 3 as

$$\text{ET or E} = P + I - R - \int_0^{\overline{Z_0}} (\theta)\, dz. \qquad (5)$$

The drainage flux density at depth z_r can be calculated by either Eq. 4 or as

$$q_{z_r} = \frac{d}{dt} \int_{\overline{Z_0}}^{z_r} (\theta)\, dz \qquad (6)$$

Potential evapotranspiration, crop factors, effective rainfall, and water use efficiency

The reference crop evapotranspiration ET_0 is the rate of evapotranspiration from a large area of uniform, 8–15 cm tall, green, actively growing grass that completely shades the soil and has ample water.

We used 10 methods to calculate evapotranspiration of the reference crop from the data collected at the meteorological station next to the experimental field: Blaney and Criddle, Jensen and Haise, radiation, Penman (original), uncorrected Penman, corrected Penman, E–pan, original Turc, simplified Turc, and Thornthwaite.

The crop (k_c) and soil (k) factors are defined as

$$k_c = (ET_{crop})/ET_0 \quad \text{and} \quad K = (E_{bare})/ET_0$$

k_c depends on the crop and its development stage. Our determinations of k_c and k assumed zero water deficit, but they did allow for effects of management practices. Crop coefficient curves were obtained by plotting k_c against crop age.

Effective rainfall was defined as the amount of rain–fall that could be used by the plants and equals total rain–fall less runoff less drainage (beyond 1 m depth). Water use efficiency is the yield (kg) per cubic metre of effective rainfall.

Crops and management practices

Our water–balance studies concentrated on maize, cowpea, munghean, and chili, which are common annual crops in Malay–sia, and represent a significant part of the total cropped area. Bare–soiland grass treatments were included as con–trols to evaluate potential evapotranspiration or reference crop evapotranspiration and to compare them with estimates based on weather data.

Plots were mulched with 3 t of cut lalang/ha. Lalang mulching performs better than other organic mulches (7), and 3 t/ha is an effective, economical rate of application. In addition to conserving water and lowering soil temperature, mulching improves infiltration rate and soil structure and reduces runoff and soil erosion (1, 4, 6, 8, 12,).

RESULTS AND DISCUSSION

Crop water balance

The calculation of water balances was based on Eq. 2, and used hydraulic conductivities determined by the internal drainagemethod.

Water balance of maize. The maize crop received 574 mm of rain in 99 d (Table 1). Except for a short dry spell in the second half of the growing season, rainfall was evenly distributed. Total runoff was 40% from maize plots and 15% from maize + mulch. For the controls, runoff was 51% from bare plots and 30% from grass. Most drainage occurred in the first 6 wk, after which drainage was minimal in all treat–ments. Range of k_c was 0.44-1.05 for maize and 0.24-0.91 for maize + mulch. Average k_c for grass was 1.02 for all ET_0 calculations. Average k (for bare plots) was 0.48, and k varied more between ET_0 calculations than between treat–ments. Effective rainfall was 45, 54, and 75% of total rain–fall for maize, maize + mulch, and grass plots. Water–use

Table 1. Components of water balance for maize and control plots.

Component	Maize	Maize + mulch	Grass	Bare
Rainfall (mm)	574	574	574	574
Runoff (mm)	230	83	17	293
Change in storage (mm)	- 42	45	23	- 7
Total drainage (mm)	88	179	125	97
Total E or ET (mm)	298	267	408	190
Av drainage (mm/d)	0.89	1.80	1.27	0.98
Av E or ET (mm/d)	3.0	2.7	4.1	1.9
Yield (t/ha)	1.13	1.81	4.04	–
Effective rainfall (mm)	256	312	431	–
% of total rainfall	45	54	75	–
Water use efficiency (kg/m^3)	0.44	0.55	0.88	–

efficiency was 0.44, 0.55, and 0.88 kg/m^3 for maize, maize + mulch, and grass.

Water balance of mungbean. In 75 d, mungbean received 625 mm of rainfall (Table 2), averaging 8.3 mm/d, which exceeded ET_0. Rainfall was uniformly distributed and no zero flux plane existed for any treatment. Mungbean plots had an average k of 0.81, with a range 0.57–1.13; for mungbean + mulch, average 0.75, range 0.38–1.24; and for grass, average 1.04, range 0.92–1.13. For bare plots average k was 0.46, range 0.34–0.55.

Mulching greatly reduced runoff and substantially increased total drainage. Effective rainfall was 42–57% of to–

Table 2. Components of water balance for mungbean and control plots.

Component	Mungbean	Mungbean + mulch	Grass	Bare
Rainfall (mm)	625	625	625	625
Runoff (mm)	222	63	48	322
Change in storage (mm)	18	9	11	3
Total drainage (mm)	115	302	218	147
Total E or ET (mm)	271	251	348	153
Av drainage (mm/d)	1.5	4.0	2.9	2.0
Av E or ET (mm/d)	3.6	3.3	4.6	2.0
Yield (t/ha)	0.83	1.13	4.30	–
Effective rainfall (mm)	289	260	359	–
% of total rainfall	46	42	57	–
Water use efficiency (kg/m^3)	0.29	0.43	1.2	–

tal rain, depending on treatment. By reducing ET at early growth stages, mulching increased water use efficiency from 0.29 to 0.43 and increased seed production. Water use efficiency of grass was 1.2 kg/m^3.

Water balance of cowpea. In 97 d, cowpea received 566 mm of rainfall (Table 3), averaging 6 mm/d. The vegetative (0–30d) and flowering periods (30–60d) were fairly dry, receiving an average 2.6 mm/d, but the podding stage was very wet, with 11 mm/d. In cowpea plots, 374 of rainfall was lost to runoff, mostly in the last 10 d of the growing season, after the leaves had wilted. Drainage beyond l m was minimal. In cowpea + mulch plots, only 3% of the rainfall was lost through runoff, and drainage correspondingly increased to 34% of the rainfall. Average evapotranspiration was 2.9 mm/d, slightly less than the 3.0 mm/d on nonmulched plots. The decrease was due mainly to lower evapotranspiration during the first 3 wk, because at later growth stages the better vegetative growth of mulched cowpea increased transpiration.

Evaporation from bare plots averaged 2.1 mm/d. Forty percent of the rain ran off and 14% (80 mm) was lost to drainage below 1 m depth. The zero flux plane method, when applicable, gave an average evaporation of 2.1 mm/d, compared with 1.9 mm/d by Darcy's Law. Both methods may therefore be used to calculate soil–water fluxes. For cowpea plots, average evapotranspiration was lower when calculated by zero flux plane method, probably because of root penetration and water extraction below the zero flus plane,

Table 3. Components of water balance for cowpea and control plots.

Component	Cowpea	Cowpea + mulch	Grass	Bare
Rainfall (mm)	464	566	566	566
Runoff (mm)	173	17	8	225
Change in storage (mm)	59	78	42	61
Total drainage (mm)	– 2	193	148	80
Total E or ET (mm)	234	278	368	200
Av drainage (mm/d)	- 0.03	2.0	1.5	0.8
Av E or ET (mm/d)	3.0	2.9	3.8	2.1
Yield (t/ha)	1.71	2.10	5.94	-
Effective rainfall (mm)	291	356	410	-
% of total rainfall	63	63	72	-
Water use efficiency (kg/m^3)	0.59	0.59	1.45	-

Average k_c for cowpea was 0.71, range 0.46 – 1.00.For cowpea + mulch, average k_c was 0.69, almost equal to that of cowpea, and range was 0.22 – 1.02.Average k for bare soil was 0.5, range 0.36 – 0.61. Values depended on whether soil was wet or dry. Water use efficiency of cowpea was 0.59 kg/m^3, and effective rainfall was 63% with or without mulch.

Water balance of chili. The first 3 wk after planting chili were dry, followed by 3 wet wk, 2 dry, and 2 wet. The third month was dry, after which it rained almost every day until the end of the experiment.

For chili plots, average ET was 4.1 mm/d, and drainage 0.3 mm/d; for chili + mulch, ET was 3.2 mm/d, and drainage 1.9 mm/d (Table 4). The chili plants and the mulch signifi – cantly reduced runoff. Drainage on the mulched plot corres – pondingly was higher. Yield, on a fresh weight basis, was about 55% higher on mulched than on nonmulched plots. Fresh – weight water use efficiency correspondingly increased 4.1 to 7.9 kg/m^3. These benefits of mulch derived from a reduction in evaporation, lower soil temperature, and improved water availability during dry periods. For chili and chili + mulch, average k_c were 0.94 and 0.74. Average k (bare soil) was 0.49.

On bare plots, evaporation was 2.1 mm/d, runoff was 52% of rainfall, and drainage (the result of a heavy shower just before planting) was significant only during the first week. Average drainage was 0.8 mm/d (13% of rainfall). A zero flux

Table 4. Components of water balance for chili and control plots.

Component	Chili	Chili + mulch	Grass	Bare
Rainfall (mm)	938	938	938	938
Runoff (mm)	261	143	232	484
Change in storage (mm)	62	66	58	28
Total drainage (mm)	36	275	400	122
Total E or ET (mm)	279	454	249	305
Av drainage (mm/d)	0.3	1.9	2.8	0.8
Av E or ET (mm/d)	4.1	3.2	1.7	2.1
Yield (t/ha)	26.5	40.9	-	-
Effective rainfall (mm)	641	520	306	-
% of total rainfall	68	55	33	-
Water use efficiency (kg/m^3)	4.1	7.9	-	-

plane existed. Average evaporation values calculated by the zero, flux plane method and Darcy's Law were each 2.3 mm/d. Average drainage estimates were 0.4 and 0.5 mm/d.

On cropped plots, drainage beyond 1.0 m was appreciable only during the last month when the soil was at field capacity after more than 300 mm rain. Depth of zero flux plane ranged from 53 to more than 120 cm. Estimates of average ET and drainage, when calculated by Darcy's Law and by zero flux plane method, were, respectively, 4.0 and 3.8 mm/d and 0.03 and 0.41 mm/d.

Formulas for evapotranspiration

Our earlier experiments showed that different evaporation formulas give different results, and that the differences between their predictions depend on the particular weather values. Because ET_0 is the reference crop (short grass) evapotranspiration, we included a cowgrass Paspalum notatum Flugge treatment, which was monitored continuously for over a year.

The most appropriate formula for ET_0 for Malaysian conditions will be that which gives k_c values as close as possible to unity. Table 5 shows that the Jensen and Haise, Thornthwaite, and Turc original methods overestimate reference crop evapotranspiration, and the other methods underestimate it. The corrected Penman formula gives values that agree very well with measured ET_0. For our experimental conditions, and particularly because of low wind speed, the pan-factor method, in which E-pan values are multiplied by crop- and weather-specific factors, did not give reliable predictions.

CONCLUSION

For maize, mungbean, cowpea, chili, and grass, average water use during crop growth was, respectively, 3.0, 3.6, 3.0, 4.0, and 4.2 mm/d.

The runoff component in the water balance equation cannot be neglected, even for almost flat areas, because of the high intensity of rainfall and the rapid slaking of topsoil. Darcy's Equation is recommended for calculating

Table 5. Crop coefficient (k_c) for grass in 5 experiments, using different methods of calculating ET_0.

Method	k_c					
	I	II	III	IV	V	Average
Blaney and Criddle	1.03	1.13	1.11	0.99	1.06	1.06
Jensen and Haise	0.79	0.79	0.81	0.70	0.86	0.79
Radiation	1.07	1.12	1.15	1.00	1.17	1.10
Penman original	1.15	1.15	1.18	1.02	1.23	1.15
Penman uncorrected	1.04	1.08	1.12	0.95	1.14	1.07
Penman corrected	1.03	1.03	1.00	0.91	1.12	1.02
E-pan	1.56	1.46	1.75	1.34	1.55	1.53
Thornthwaite	0.94	0.87	0.92	0.78	0.95	0.89
Turc original	0.89	0.97	0.92	0.80	0.99	0.91
Turc simplified	1.05	1.08	1.08	0.94	1.14	1.06
Average	1.02	1.04	1.06	0.92	1.10	1.03

Table 6. Components of water balance for mulch and no-mulch treatments for 4 crop species.

Component	Maize		Mungbean		Cowpea		Chili [a]	
	No mulch	Mulch	No mulch	Mulch	No mulch	Mulch	No mulch	Mulch
Runoff (mm)	230	83	222	63	173	17	261	14
Drainage (mm)	88	179	115	302	- 2	193	36	275
Evapotranspiration (mm/d)	3.0	2.7	3.6	3.3	3.0	2.9	4.0	3.2
Yield (t/ha)	1.13	1.81	0.83	1.13	1.71	2.10	26.5	40.9
Effective rainfall (% of total)	45	54	46	42	63	63	68.3	55.4
Water use efficiency (kg/m^3)	0.44	0.55	0.29	0.43	0.59	0.59	4.1	7.9

[a] Fresh weight basis.

soil–water fluxes and hence water balances. The zero flux plane method also gave accurate results, but for Malaysian weather conditions the zero flux plane exists for short periods only. Lalang mulch at 3 t/ha improved crop yield in all treatments, and increased water use efficiency by as much as 90% (Table 6). Mulching lowered temperature at 5-cm soil depth by 5 to 10 K.

The corrected Penman Equation was the most suitable for predicting ET_0 under Malaysian conditions.

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POSTER ABSTRACTS

WATER-SAVING IRRIGATION TECHNIQUES FOR SOYBEAN AFTER RICE

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Field experiments were conducted at Sukamandi and Mojosari Experiment Farms to develop water-saving techniques for soybean cultivated in dry season after lowland rice.

Soil texture, CEC, clay content, and pH differed between the two farms. Sukamandi soil was a nonexpanding clay and needed a higher soil-water content to maintain the same soil-moisture regime as the Mojosari soil.

Soil moisture equivalent to pF 3.2-3.7 was adequate for good soybean yields. Incorporating 8 t animal manure/ha increased the water-absorbing capacity of Sukamandi soil. On Mojosari soil, straw mulch had the same effect, but poor drainage reduced soybean yield.

WETLAND UTILIZATION RESEARCH PROJECT

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The Wetland Utilization Research Project (WURP) seeks to develop low input technologies of soil, water, and crop management for intensive utilization of small inland valleys for smallholder rice-based farming systems in West Africa.

Four categories of West African wetlands were distinguished and inventoried. Based on physical and agrosocioeconomic criteria, six areas for benchmark sites were identified in Sierra Leone, Ivory Coast, Togo, and Nigeria. Valley sites for research investigations have been identified in Sierra Leone and Nigeria.

Initial findings for Sierra Leone (Makeni-Magburaka area) showed that agrosocioeconomics, water management, and soil management were constraints to development. Soil constraints were poor physical performance of mainly sandy soils, low inherent fertility, a problematic N mineralization cycle, and Fe toxicity.

WURP is a collaborative project of the International Institute of Tropical Agriculture, Nigeria, and the International Institute for Land Reclamation and Improvement, the Netherlands Soil Survey Institute, and the Royal Tropical Institute in The Netherlands.

SYSTEMS ANALYSIS AND SIMULATION FOR RICE PRODUCTION: A RESEARCH AND TRAINING PROJECT

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The use of systems analysis and simulation techniques in agriculture facilitates integration of knowledge from different scientific disciplines, predicts crop growth and water use in untested conditions, and accelerates application and transfer of knowledge.

Goals of the project are to combine rice crop data with existing (non-rice) crop growth and water balance simulation models, and to disseminate information to agricultural universities and experiment stations and to train national program scientists in simulation modeling.

A training course on rice production modeling for eight teams of three participants is scheduled. During the year following the course, teams will receive continuing scientific and technical support to help develop national program infrastructures for research that combines both simulation and experimentation.

RICE RESEARCH IN SRI LANKA

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Agricultural training and research programs in Sri Lanka are being carried out by the Postgraduate Institute of Agriculture, Peradeniya. Eighteen of 36 scholars have completed their courses and have found employment.

Research topics are chosen to suit local development projects. Ongoing studies include water requirements of rice for three Sri Lankan reservoir irrigation schemes. At each scheme a specific constraint such as salinity or weed control in dry seeded rice has been selected for special emphasis. Other studies include N fixation of soybean and cowpea on poorly drained soils.

CHARACTERIZING WATER MOVEMENT

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Six methods of measuring hydraulic characteristics of field soils are used at the Netherlands Soil Survey Institute. They are the column method, the cube method, the drain–cube method, the crust test, and the short–circuiting (bypass flow) method, and a method for measuring effects of horizontal cracks.

There is a need to make more field measurements using large, undisturbed samples rather than small core samples that are transported to and measured in the laboratory.

SEEDING TECHNIQUES AND MACHINERY

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Development and use of equipment for seedbed preparation and planting in low–moisturesoils usually seeks to improve the timeliness of operations for optimum plant establishment and soil moisture conservation. Seeding techniques are needed to improve work rates and to reduce the risk of seed/seedling failure. The availability of selective herbicides has encouraged development of seeding methods based on conservation tillage. They provide an alternative to conventional tillage, which consumes substantial time and energy.

Fundamental relationships between seeds and in–groove soil microenvironments during early crop establishment in untilled soils are reviewed. Machinery specifications are given for seed groove opening, seed and fertilizer placement, sowing depth, groove closure, soil and seed firming, trash clearance, and herbicide application for dry and moist soils.

Seeding and related machinery have been designed and fabricated based on soil-seed-machinery interactions. The machinery may be suitable for establishing follow-on crops in rainfed rice-based cropping systems.

SOIL FRIABILITY AND WETTING AND DRYING CYCLES

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Soil friability -- the tendency of a mass of unconfined soil to break down and crumble under applied stress into a particular size range of smaller fragments -- can be measured by simple crushing tests on aggregates. Weakest-link theory shows that tensile strength is related to aggregate diameter and friability index.

Friability is due to microcracks and other structural features within the aggregates. Soil in poor structural condition lacks these features and has friability index <0.1. Soil in good condition has an index >0.3. Wetting and drying cycles and chemical amendments, such as gypsum, can increase friability. There are critical rates of wetting for increases in friability to occur. Wetting can induce microcracks in particular directions, thus causing anisotropy of friability.

WATER AND NITROGEN BALANCES OF DRYLAND CROPS FOLLOWING LOWLAND RICE

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Water stress and N cycling are being studied to identify optimum management for dryland crops. At Reading, England, root growth of young mungbean and cowpea plants is being assessed under controlled conditions in relation to soil physical properties. Field studies at IRRI are evaluating water and N balances of rice and dryland crops in relation to sowing time and planting density of the dryland crop. Results of laboratory and field experiments are being incorporated into crop production models.

EFFECT OF RICE-BASED CROPPING SEQUENCES ON SOIL PHYSICOCHEMICAL PROPERTIES

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Effects on soil physicochemical properties of rice-based cropping sequences were tested in four 3-yr rotations in Guangdong:

- wheat-rice-rice, astragalus-rice-rice, fallow-rice-rice;
- wheat-rice-rice, astragalus-rice-rice, bean-rice-rice;
- wheat-peanut-rice, astragalus-rice-rice, pea-rice-rice; and
- wheat-rice-sweet potato, astragalus-rice-rice, fallow-rice-rice.

Good soil structure, as represented by an empirical index, correlated with crop response to applied fertilizer. Yearly total crop yield also correlated with soil carbon dioxide, percolation rate, total N, available P, and alkali-hydrolyzable N. Carbon dioxide content correlated with crop yield, perhaps reflecting the level of biological activity and the related soil nutrient supply. Soil aggregation and structure were improved by organomineral complexes.

INTERNATIONAL NETWORK ON SOIL FERTILITY AND FERTILIZER EVALUATION FOR RICE (INSFFER)

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INSFFER promotes research and cooperation to increase fertilizer use efficiency and to improve and maintain soil fertility levels that will sustain high rice yields. National program scientists, IRRI, and the International Fertilizer Development Center (IFDC) collaborate in research trials, training, and site visit tours.

Twelve collaborative research trials deal with topics that include fertilizer efficiency, long-term fertility, P sources, acid soils, azolla, and integrated use of inorganic and organic fertilizers.

Training, both theoretical and practical, aims to strengthen the capabilities of INSFFER researchers and technicians. In site tours and workshops, cooperators observe INSFFER trials and characterize the sites visited. Significant findings are tested at larger scale in farmers' fields.

MICROMORPHOLOGICAL STUDIES OF RICE SOILS IN ITALY AND MALAYSIA

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Porosity, shape, and size distribution of pores were measured on thin sections of undisturbed soil samples by electrooptical image analysis. Total porosity generally increased, and pore number decreased during rice culture. Total porosity was higher in Ap horizons than in Aps horizons where a densely packed soil layer or plowpan was common. Modifications of pore shape patterns were observed. Planar (elongated) pores predominated in most soils.

Light microscopy of thin sections showed diffusion organoferrans and ferrans, diffuse Fe-Mn concentrations, and ferric rings around plant roots. There were some differences among soils. These pedological features may relate to fertility and structure of rice soils. Variations of topsoil texture also were observed.

NO-TILL SOYBEAN PRODUCTION AFTER RICE

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Large areas of Sumatra remain fallow after harvest of rainfed or partially irrigated rice. Those fallow lands were evaluated for growing no-till dryland crops after rice. Additional experiments sought to identify optimum cultural methods for soybean.

Following rice, soybean performed best at 20- x 20-cm spacing on mulched, untilled fields with 22 kg N/ha and

20 kg P/ha. Soybean yields were affected by planting date, total rainfall, and rainfall distribution. Monthly rainfall above 80–100mm reduced soybean yield.

Of the varieties tested, some local land races performed as well as national improved cultivars.

PHYSICAL ASPECTS OF RICE SOILS IN MALAYSIA

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Although few data have been collected, physical aspects of rice soils have increasing importance for mechanization and water management in Malaysia, especially for direct seeding.

In Malaysia, rice is grown on marine and riverine soils and organic clays. Marine soils are predominantly smectitic and riverine soils are kaolinitic. Rice yields average 3–5 t/ha on marine soils and 2–3 t/ha on riverine soils. Riverine soils have higher bearing capacity, with a cone index value of 0.9 MPa as compared to the 3.5 MPa of marine soils. However, the plowsole in marine soils is thicker than in riverine soils, although the depth of the plow layer is the same.

When small, uneconomic fields are enlarged and leveled, fertile organic topsoil is removed, sand and gravel layers are exposed, and there is excessive loss and uneven distribution of standing water. Soil fertility has decreased, and yields are very low.

AGROHYDROLOGY OF UPLAND RICE

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IR36 was grown on a gently sloping upland toposequence underlain by a shallow water table. Depth to groundwater, soil water content and potential, soil nutrient concentrations, and plant height were monitored frequently in 1983 and 1984 wet seasons.

In 1983 wet season, which had a relatively long rainless period, increments of plant height and final grain yield each showed a dependence on upslope position. These dependences may have resulted from a systematic variation in groundwater contribution to crop water use, or from down–slope migration of N fertilizer after a typhoon.

In 1984, many more rain days caused persistently high soil moisture. Soil wetness delayed essential weeding, and may have caused substantial nutrient leaching. Orange leaf virus was prevalent. Perhaps because of these complications, neither growth increments nor grain yields showed consistent dependence on hillslope position, or on the presence or absence of wooden, cross–slope erosion barriers.

TILLAGE IN RAINFED LOWLAND RICE–BASED CROPPING SYSTEMS

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In field experiments, the dense layer in a puddled Typic Tropaquept rice soil was disrupted by a chisel tine along strips 0.5 m apart. Tillage was immediately after a simulated rice harvest, and seeds of dry season crops were planted in the tilled strips. Cohesion and friction coefficients were less, and roots penetrated more rapidly to the wet subsoil in the tilled strips than in untilled or conventionally tilled soil.

Mungbean roots reached 60–cm depth 2 wk earlier in plots cultivated in strips by a single tine (whether pulled by a tractor or a prototype cable–winch system) than in conventionally tilled plots. Below tillage depth, root density was affected by natural horizons of higher shear strength. For maize, excavated roots extended more widely along the tilled strips than at right angles to them.

For mungbean planted at minimal (4 d) delay after the simulated harvest, grain yield was 2.1 t/ha for strip tillage and 1.9 t/ha for conventional tillage. There was little rainfall, and crops essentially grew on stored soil water. The high yields were partly from precision manual seed planting. The uniformly emerged crop used solar irradiance and soil water effectively. Crops also made good use of the available depth of soil above the natural horizon of higher shear strength. Each 13 cm of additional root depth was associated with 100 kg/ha more grain yield.

EFFECTS OF GREEN MANURES AND CROP RESIDUES ON SOIL PHYSICAL PROPERTIES IN RAINFED LOWLAND RICE-BASED CROPPING SYSTEMS

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In two experiments on silty clay loam soils, measurements were made of the effects of incorporated crop residue and legume green manures on soil physical properties. Legumes were grown immediately before rice in the crop sequences, and were known nutritionally to benefit rice. Measurements were made after 1 yr and after 4 yr of the cropping sequence.

Incorporating green manures for 4 yr may have slightly affected topsoil porosity and water infiltration rate. But effects were small in relation to the inherent spatial variabilities of soil parameters. Infiltration rate at legume incorporation was so high on both manured and unmanured plots as to imply a need for effective puddling that would impound water for the following rice crop.

After one year's incorporation of maize and soybean residues, subsoil shear strength (at 2 MPa cone index value) was high enough to impede rooting of rice and dryland crops. Mohr-Coulomb parameters of cohesion and internal friction, and saturated hydraulic conductivity were not changed.

LAND PREPARATION FOR DRY SEEDING ON PROBLEM SOILS

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In Vietnam, most rainfed saline or moderately acid sulfate soils are planted to only one crop of long-duration traditional rice a year. Farmers wait until heavy rains have softened the previously puddled soil and flushed away the toxic salts before plowing and harrowing. Growing an extra short-duration, modern variety by direct wet seeding or transplanting often is risky because irregular rains hamper stand establishment on hard, cracked, puddled soils. A dry seeding procedure can minimize that risk.

Land is plowed when it hardens after the wet season crop is harvested. That prevents ratooning, weed growth, and capillary rise of toxic salts. It also helps the soil to dry and speeds organic matter decomposition. When the plowed soil is dry, fields are harrowed. Shallow drainage ditches are constructed at 10- to 15-m intervals to help flush out toxic salts.

Short-duration, adverse-soils-tolerant varieties are broadcast, row-drilled, or hill-dibbled and the seeds covered by harrowing. Drains are kept open during the first month of growth.

When the crop is harvested, as much straw as possible is removed to avoid the adverse effect of soil reduction, the soil is puddled, and a traditional, long-duration crop is planted.

EFFECT OF FLOODING DURATION ON RICE SOIL STRUCTURE

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Soil of triple-cropped (rice - rice - wheat) fields in the Tai-hu lake region of China has been compacted through prolonged flooding and cultivation for rice. The effects on rice soil structure of flooding duration and tillage were studied in an incubation experiment under natural conditions.

Prolonged flooding substantially decreased both soil aggregation and the >200 mm pore space. It increased the modulus of rupture. These effects were amplified, and the soil compacted, when the flooded soil also was tilled.

Changing from rice - wheat to rice - rice - wheat sequences therefore damages soil structure.

SOIL PHYSICAL CONSTRAINTS TO RICE PRODUCTION IN BANGLADESH

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Soils in Bangladesh range from perennially wet, poorly developed, and hydromorphic in floodplains to well-drained, deep-red Latosols in upland terraces and hills, Soil physical constraints to rice growth include low water-holding capacity and shallow plowpans that limit water infiltration and crop rooting in dry season and promote erosion in wet season. A 2- to 3-cm-thick plowpan at 7-10 cm depth has developed to some degree in almost all puddled soils.

Silty loam and silty clay loam soils of the Ganges floodplain have high hydraulic conductivity at saturation, which drops sharply with decreasing moisture content. The silty clay and clay soils have insufficient available water for winter crops. Soils of Barind and Modhupur Clay range from clay loam to clay. They have low conductivity and are suited to wet season transplanted rice, but retain insufficient moisture for winter crops.

Tillage in Bangladesh is constrained by heavy topsoils, by plowpans, and by plowpans underlain by subsoil with low bearing capacity. Experiments showed that deep tillage (5 – 20 cm) promoted deeper root growth and increased uptake of residual soil moisture by dryland crops.

RECOMMENDATIONS

Workshop participants concluded that there is substantial potential for developing practical technologies to increase food production from lowlands employed for rice-based cropping systems. Applied research on physical aspects of soil management that now limit food production is a key component in developing those technologies. In working group sessions, workshop participants drafted the following recommendations.

POLICY AND TRAINING

- To optimize rice production and maximize water availability for crops grown after rice, applied research on physical aspects of soil management should be substantially increased. The research must be closely integrated with other work on crop production, and must include interdisciplinary activities involving physicists, soil scientists, engineers, agronomists, and crop physiologists.

- The diversity of soils and agroclimates in rice producing areas requires that research be conducted at many sites. National research programs in developing countries must play a major role in the needed studies.

- There are too few scientists with training in the physics of soil and crop management. Thus:
  - information about physical soil improvement programs must be compiled and published to increase awareness of the need for training;
  - assistance must be provided for graduate studies in soil physics and physical chemistry of soils;
  - in-country, on-the-job training courses and staff development through short-term courses are needed. Training for soil-physics laboratory and field technicians should be emphasized.

- A network system, either as an additional component in an existing network or as a new network, is needed to optimize use of resources for research and training. Networking will enable prompt and effective communication of results, techniques, and experiences to researchers in participating national programs.

- Proper characterization and classification of all research sites are essential for interpreting and extrapolating results. Therefore:
  - a methodology for the physical aspects of such characterization should be developed;
  - a working group should be established to develop standardized soil physical measurements for lowland soils and to initiate a system of interlaboratory comparisons; guidelines and results of comparisons should be widely distributed;
  - a classification system should be developed to meet requirements for differing levels of detail and with emphasis on physical characteristics;
  - guidelines should be developed for interpreting site characterization data in relation to implications for sustained rice production, soil and
  - water management, and production of nonrice crops after rice;
  - the influence of soil fauna on physical characteristics should be further studied and included in the characterization;
  - existing sites should be selected on which to evaluate the proposed classification system;
  - the cooperation and assistance of appropriate organizations such as Soil Management Support Services in characterizing and classifying sites that represent important riceland conditions should be sought to ensure that appropriate locations are selected for off-stationfield experiments;
  - there should be a program to train personnel in site selection and characterization.

RESEARCH

Recommendations are summarized according to problems suited to network-type research, and to problems requiring more detailed and specialized investigations.

Network–type research needs

Puddling and related problems:

- characterize for different soils the physical conditions that favor plant growth, and determine ways to achieve them;
- determine methods of developing suitable soil structure for dryland crops grown after rice on puddled soil;
- evaluate the potential of zero tillage for rice–based cropping systems;
- evaluate and compare different puddling methods used by farmers on different soil types.

Pans, the need for them, and their manipulation and management:

- study the development and depth of pans, modification of pans by physical or chemical methods, and effects on permeability, aeration, and on root development and yield of rice and dryland crops grown after rice;
- investigate bearing and shearing strengths of pans, and their optimum ranges.

Percolation–related problems:

- determine the ranges of hydraulic conductivity that best suit rice crops, and evaluate methods to control percolation and seepage, especially after dryland crops;
- develop strategies to conserve water and control water table levels;
- investigate effects of percolation on aeration and soil structure, on nutrient losses, and on toxin removal and salinity control.

Use and management of crop residues and other organic resources:

- investigate management methods and soil physical effects of organic matter -- including effects on soil structure;
- determine nutrient value and optimum and harmful concentrations of soil organic matter, and the effects of quality of organic matter on crop yields and soil biological activity;
- examine the potential for exploitation of Histosols.

Watershed management and toposequence relations:

- monitor at all levels in the topography, water, soil, and nutrient flows that affect rice production;
- determine the limits imposed by topography, elevation, and soil type on the practice and practicality of flooding terraced fields;
- quantify effects of soil erosion and nutrient losses by leaching, and their effects downslope.

Specialized research needs

- study the development and removal of toxic products resulting from organic matter decay under flooded conditions;
- determine the relay and cropping sequences that optimize utilization of seasonal water and radiation;
- determine, by specialized techniques, the vertical and lateral water flows in different landscape positions;
- investigate the effects of heat flow and transport and of other physical properties on germination and root growth, and categorize such properties;
- develop biophysical simulation models of rice-based cropping systems to evaluate effects of soil physical properties on yields (supported as necessary by lysimetry and controlled-environment studies);
- investigate the mechanics and physicochemical processes of pan formation;
- establish guidelines for tillage for rice and rice-based cropping systems for major riceland soils;
- undertake controlled-environment studies of root development (and supplementary field studies) to identify impediments to growth, and establish procedures for managing those impediments;
- develop machines, which are suitable for local fabrication and maintenance, for direct seeding, minimum and other tillage practices, residue management, and fertilizer placement for rice and subsequent dryland crops;
- investigate the influence of organic matter (quantity, quality, and distribution) on soil physical properties such as structure, permeability, workability, and erodibility.

IMPLEMENTATION

To achieve the preceding recommendations, it was agreed that:

1. IRRI should prepare and distribute to all workshop participants and interested individuals and organizations a report of the workshop and its recommendations, and should promptly publish the workshop proceedings.
2. A working group, comprising IRRI, the International Board for Soil Research and Management (IBSRAM), and national program representatives, shall determine by correspondence and, if necessary, through an early meeting, the strength of interest in coordinated research and information interchange -- especially for research that requires multilocation experimentation across a range of soils.
3. The working group shall cooperate and communicate with those donor agencies that have expressed interest in funding coordinated research in physical aspects of soil management.

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