AGENCY FOR INTERNATIONAL DEVELOPMENT
WASHINGTON, D. C. 20523

BIBLIOGRAPHIC INPUT SHEET

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1. SUBJECT CLASSIFICATION

A. PRIMARY: Agriculture — AF22-0000-GG50

B. SECONDARY: Soil chemistry and physics--Tropics

2. TITLE AND SUBTITLE

Puddling tropical rice soils

3. AUTHOR(S)

Sanchez,P.A.

4. DOCUMENT DATE: 1971

5. NUMBER OF PAGES: 16p.

6. ARC NUMBER: ARC 631.587,S211

7. REFERENCE ORGANIZATION NAME AND ADDRESS

Cornell

8. SUPPLEMENTARY NOTES *(Sponsoring Organization, Publishers, Availability)*

(In Soil science,v.115,no.2,p.149-158 and no.4,p.303-308)

9. ABSTRACT

10. CONTROL NUMBER

PN-RAA- 543

11. PRICE OF DOCUMENT

12. DESCRIPTORS

Assimilation
Nitrogen
Puddling
Rice
Tropics
Water loss

13. PROJECT NUMBER

14. CONTRACT NUMBER

CSD-2834 211(d)

15. TYPE OF DOCUMENT

AID 590-1 (4-74)

SOIL SCIENCE
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Vol. 115, No. 2
Printed in U.S.A.

PUDDLING TROPICAL RICE SOILS: I. GROWTH AND NUTRITIONAL ASPECTS[1]

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Received for publication April 5, 1972

The vast majority of the world's tropical rice is produced under lowland conditions characterized by the practices of flooding, puddling, and transplanting. The advantages and limitations of flooding and transplanting are well established (Matsubayashi et al. 1967; Ponnamperuma 1965). In contrast, the influence of soil puddling on rice performance has received little quantitative attention although this ancient practice is widely considered beneficial for rice production (Birkinshaw 1940; Grant 1965; Izumi 1966; Stout 1966; Van de Goor 1950a).

REVIEW OF THE LITERATURE

Soil puddling in rice fields consists of harrowing the top 10 to 15 cm at moisture contents above field capacity until most aggregates are destroyed and the soil is transformed into a slurry that flows. Laboratory studies show that most of the noncapillary pore space disappears while capillary pore volume increases (Bodman and Rubin 1948; Jamison 1953). Puddling increases soil moisture contents at a given tension (Croney and Coleman 1954), decreases water losses by evaporation (Buehrer and Aldrich 1946) and decreases soil aeration (Aomine and Shiga 1959; McGeorge and Breazeale 1938). Many papers mention that puddling reduces percolation; however, no quantitative comparison between puddled and undistrubed soils are available (Birkinshaw 1940; Izumi 1966; Koenigs 1963; Sakanoue and Matsubara 1967; Van de Goor 1950a). Although no adequate measurements of the degree of puddling are available in the literature, it is known that substantial variability exists within a paddy field (Briones and Raymundo 1962), among local cultural practices and several soil properties (Allman and Kohnke 1948; Buehrer and Aldrich 1946; Buehrer and Rose 1943; Harris, Chesters, and Allen 1966; Koenigs 1961; Koenigs 1963). The puddled layer is divided into several subhorizons (Aomine and Shiga 1959) particularly in loamy soils (Izumi 1966). A relatively impermeable layer formed immediately below the puddled horizon has been attributed to compaction during the puddling process and illuviation of reduced Fe and Mn compounds (Grant 1965; Koenigs 1950). These "plow pans" are found in loamy soils grown to rice for many years, in well-drained latosols, and as concretionary materials in andosols (Grant 1965) but are absent in sandy and clayey soils, vertisols, young alluvial and calcareous soils (Grant 1965; Moorman and Dudal 1964; Stout 1966).

Puddling per se can produce soil reduction in the absence of flooding (Breazeale and McGeorge 1937; Frapps and Sterges 1937). The well-known consequences of soil reduction and their relationships to rice growth (Ponnamperuma 1965) may therefore take place in unflooded puddled rice soils although the number of and intervals between harrowing operations may significantly disturb the kinetics of reduction during the land preparation process. It is believed that puddling hastens the mineralization of soil organic matter (Izumi 1966; Sakanoue and Mizunuma 1962). Significant increases in NH_4^+-N production after four weeks of anaerobic incubation were observed in puddled soil samples in relation to flooded b undisturbed counterparts (Harada, Hayashi, and Chikamoto 1964; Sakanoue and Matsubara 1967). Increases in N uptake by rice under puddled conditions were also reported by these authors. Another

[1] Agronomy paper No. 976. Contribution of the Agronomy Department, Cornell University. Based on a portion of the author's dissertation under the auspices of the University of the Philippines-Cornell University Graduate Program sponsored by the Ford Foundation. The author is grateful to Dr. Richard Bradfield, International Rice Research Institute, for his supervision.

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study[3] reports increases in soil N mineralization with puddling up to two weeks of incubation, but the effect disappeared afterwards. Nitrogen uptake by four-week-old rice plants did not show effects of puddling. Briones' data suggest that puddling increases N mineralization temporarily just like other aggregate disruption treatments (Rovira and Greacen 1957). The availability of other nutrient elements, particularly of P, is thought to increase with puddling (Grant 1965; Koenigs 1961; Koenigs 1967; Stout 1966).

Soil puddling is also considered advantageous to rice growth because it (a) reduces initial weed infestations (Van de Goor 1950a[4]), (b) facilitates land leveling (Shapiro 1958), and (c) permits the farmers to work the soil regardless of moisture status (Bradfield 1969).

The effects of puddling in crops other than rice are clearly detrimental (Dutt 1948; McGeorge and Breazeale 1931; McGeorge and Breazeale 1938). Experimental evidence with rice is scarce. A study conducted on a well-drained latosol near Bogor, Indonesia, compared the conventional puddling practice of tillage with excess water with tillage at field capacity (Van de Goor 1950a). The average yields of two rice varieties were 2.1 and 1.7 tons/ha, respectively. An experiment in Japan also compared the conventional puddling practice with dry plowing followed by flooding, which resulted in the formation of hard clods (Sakanoue and Mizunuma 1962). Transplanted yields averaged 3.5 and 2.3 tons/ha respectively. The lower yield of the dry-tilled treatment was attributed to N leaching losses which were substantiated by soil NH_4^+ levels and plant N uptake. In the Philippines, increasingly higher rice yields were obtained by increasing the intensity of puddling operations from zero tillage to 12 passes with harrows.[4] These three experiments suggest that rice performance is superior with a more thorough degree of puddling but do not prove that a puddled soil is a better medium for rice growth than a well-granulated one.

The necessity of puddling tropical rice soils by small Asian farmers has been questioned by Bradfield (1969) who suggested that rice be grown in well-granulated soils during the rainy season and be followed by a series of other crops to provide a more adequate diet.

The purpose of this investigation is to compare rice performance under puddled and well-granulated soil conditions in terms of (a) growth and yield, (b) nutrient uptake, (c) nitrogen movement and losses, (d) water movement and losses, and to determine the advantages and limitations of soil puddling. The first three aspects are evaluated in this paper and the fourth in a subsequent one.

EXPERIMENTAL

A series of experiments were conducted in Los Baños, Philippines (14°10'N, 38 m elevation), in order to achieve the above objectives. The pot and barrel experiments were conducted in an outdoor screenhouse at the Soils Department of the University of the Philippines. The field experiments were conducted at the International Rice Research Institute farm.

1. *Growth and nutrient uptake under flooded conditions*

Rice growth and nutrient uptake patterns were compared under puddled flooded and granulated flooded conditions in five soils representative of Philippines lowland rice farms (Table 1). The treatments were arranged in a randomized complete block design with two replications.

The soils were subjected to several wetting and drying cycles designed to achieve a maximum degree of granulation. The 4.5-kg samples of air-dry soils were passed through a 1-cm^2 mesh sieve, placed in 5-liter clay pots, and wetted to saturation from below. Puddling was accomplished by hand until a degree similar to field puddling was attained. Eight pregerminated PI-21593 rice seeds were sown directly. All pots remained flooded from 15 days after seeding to harvest at an average depth of 3 cm above the soil surface. A total of 136 ppm N as $(NH_4)_2SO_4$ split in three applications was the only fertilizer added. No drainage was allowed throughout crop growth. Height and tiller pro-

[3] Briones, A. M. 1966. Nitrogen availability in five soils under different management systems and its effect on growth and yields of rice. M. S. thesis, University of the Philippines College of Agriculture, Los Baños. 107 pp.

[4] Deomampo, N. R. 1968. An economic analysis of tillage, weeding and nitrogen interaction on yield of rice. M. S. thesis, University of the Philippines College of Agriculture, Los Baños. 287 pp.

TABLE 1

Characteristics of the five soils used in the first experiment (A horizon)

Soil type	Classification	pH	% Organic Matter	% Total N	CEC	Ca	Mg	K	Bray 2 P ppm
					me/100 g				
Maahas clay	Andeptic haplaquoll	5.7	2.85	0.137	34.9	19.4	5.9	1.8	11.6
Quingua clay	Typic tropaquept	5.9	1.73	0.072	29.6	18.8	9.9	0.3	4.4
Faraon clay	Typic argiaquoll	7.0	4.24	0.197	44.5	33.8	4.8	0.6	18.6
Buenavista clay loam	Typic ustropept	5.7	1.67	0.083	20.3	13.6	3.4	0.3	3.2
Isarog silty clay	Typic dystranddept	5.1	10.71	0.303	36.2	5.4	2.5	1.2	5.4

duction was counted weekly. Dry matter production and the uptake of N, P, K, Fe, Mn, and Si were determined according to standard procedures at 27, 68, 83, and 111 days after seeding which corresponded to the tillering, panicle initiation, flowering and maturity stages. Water consumption during the last 60 days of growth was computed as the sum of daily additions plus rainfall.

2. *Field comparisons between puddled and granulated soil management practices*

The structural variables studied in the first experiment were compared at the field level in the Maahas soil during the rainy season. Two cropping systems, the traditional puddled-transplanted practice and direct seeding in well-granulated soils, were compared at three levels of applied N (66, 91, and 116 kg N/ha) in 400-m^2 plots arranged in a split-plot design with two replications. The short-statured IR52-18-2 selection was transplanted by hand at 25- × 25-cm spacing in the puddled-transplanted system and drilled in 30-cm rows with a tractor at a rate of 30 kg/ha in the well-granulated soil. A basal application of 66 kg/ha and 40 kg P_2O_5/ha was incorporated in the topsoil prior to seeding or transplanting on both treatments. The remaining N was topdressed at the panicle-initiation stage. The conventional puddled treatment was flooded a week after transplanting and remained so until harvest. The granulated treatment was kept unflooded until the fifth week of growth, after which it received the same water management as the puddled counterpart. Heavy rainfall kept the subsoil saturated with water during the growing season. Growth characteristics and N uptake were measured at the tillering, panicle-initiation, and maturity stages. The comparisons in this experiment are between soil management systems characterized by soil structural conditions and not between puddled and granulated soils per se.

3. *Effects of puddling—water table interactions on rice growth and nitrogen relationships*

A factorial design consisting of two soils, two water-table levels, and two topsoil physical condition levels (puddled and granulated) was arranged in a randomized complete block design with two replications. The Maahas and Faraon soils were selected according to previous experimental results. The water-table levels were 5 cm above the soil surface and 15 cm below the soil surface. The experiment was conducted in specially designed 55-gallon barrels equipped with a water-table-measuring device. The soils were sampled by genetic horizons which were subjected to similar pretreatments as in the previous experiment and placed in the barrels above a gravel layer. The A horizon was puddled at a depth of 15 cm in the appropriate treatments. A rice and a sorghum crop were grown prior to this experiment. Hakkoda rice seeds were directly sown along a circumference 30 cm in diameter during the dry season. A basal application of 100 ppm N, P, K was thoroughly mixed with the A horizon prior to planting. A topdressing of 25 ppm N was applied at

the panicle-initiation stage. The ammonium sulfate source was enriched with a one percent atom-excess N^{15} mixture. The water-table differentials were established at 14 days after seeding. Water-table fluctuations were recorded three times daily and corrected to the +5- and −15-cm levels. The amounts of water added or drained to maintain the desired water-table levels including rainfall were recorded. Plant measurements were conducted in a similar way as before. Plant samples were obtained at 30, 58, and 81 days after seeding which corresponded to the panicle initiation, 50 per cent flowering, and maturity stages in this early-maturing variety. The N^{15} analysis was performed by the International Atomic Energy Agency in Vienna.

RESULTS

1. *Growth and nutrient uptake under flooded conditions*

During the first month, plants on all puddled treatments showed more growth vigor, which was associated with significantly higher dry matter production in all soils and nutrient uptake differences in some cases (Table 2). These differences disappeared to a large extent two weeks later and completely at harvest (Table 3). No significant differences in grain and straw yields, total dry matter, water consumption, or in the uptake of N, P, K, Mn, and Si between puddled and granulated treatments were observed in four soils. Relatively small but sometimes statistically significant differences were noted in the calcareous Faraon soil, which suggested a possible beneficial effect of puddling at harvest. These differences seemed associated with a higher plant-N status at the maximum tillering stage. Rice performed almost identically in puddled and granulated systems in the other four soils, in spite of extreme P deficiency symptoms in the Buenavista and Isarog soils.

2. *Field comparison between puddled and granulated soil management systems*

Both treatments showed vigorous initial growth. At the maximum tillering stage, plants grown on the granulated treatments were taller, tillered more, and produced more dry matter than in the puddled counterparts. Plant N contents were higher in the puddled plots although both treatments were well above critical levels (Table 4). Nitrogen uptake at this stage was almost identical.

A week after the granulated treatments were flooded, plants began to show N deficiency symptoms which were quantified at the panicle-initiation stage (Table 4). The granulated treatments required more frequent applications of irrigation water than the puddled ones. The

TABLE 2

Effects of soil physical condition on growth and mineral nutrition of 27-day-old rice plants growing in flooded systems

Soil	Physical Condition	Dry matter (g/pot)	% N	% P	% K	ppm Fe	ppm Mn	% SiO_2
Maahas	Puddled	0.65	2.70	0.47	3.65	540	928	12.3
	Granulated	0.50	2.46	0.41	3.80	420	256	14.9
Quingua	Puddled	0.57	2.36	0.36	3.60	264	1408	10.6
	Granulated	0.43	3.35	0.35	3.24	271	802	11.0
Faraon	Puddled	0.56	3.66	0.24	3.70	—	—	9.5
	Granulated	0.28	3.63	0.23	3.74	310	456	8.2
Buenavista	Puddled	0.19	2.88	0.10	3.15	298	2049	—
	Granulated	0.18	2.94	0.16	4.53	720	2716	9.0
Isarog	Puddled	0.28	2.74	0.11	3.86	278	615	7.8
	Granulated*	0.15	1.99	0.13	2.59	923	400	9.1
Mean	Puddled	0.45	2.87	0.26	3.39	345	1090	10.0
	Granulated	0.31	2.87	0.26	3.58	529	926	10.5
	$HSD_{.05}$	0.07						
	CV(X)%	21						

* Visual phosphorus deficiency symptoms observed.

TABLE 3

Effect of soil physical condition on rice yield, dry matter production, nutrient uptake at harvest, and water consumption on five flooded soils

Soil	Physical Condition	Grain Yield g/pot	Straw Yield g/pot	Total Dry Matter g/pot	N mg/pot	P mg/pot	K mg/pot	Mn mg/pot	SiO_2 g/pot	Water Consumption Last 60 Days cm/pot
Maahas	Puddled	18.7	20.3	39.0	205	27.1	527	35.2	4.8	104
	Granulated	18.0	23.1	41.1	201	77.0	554	23.9	5.1	101
Quingua	Puddled	21.9	21.3	43.2	260	95.2	482	17.3	4.4	117
	Granulated	22.0	23.4	45.4	269	104.4	566	18.4	4.6	119
Faraon	Puddled	29.6	24.7	54.3	361	53.1	554	6.8	4.5	109
	Granulated	25.2	21.1	46.3	318	64.5	517	8.2	4.4	96
Buenavista	Puddled*	14.4	13.7	28.1	282	19.7	344	4.2	2.7	88
	Granulated*	15.3	13.2	28.5	251	19.8	355	9.3	2.8	77
Isarog	Puddled*	11.5	10.9	22.4	170	27.2	289	5.1	2.3	95
	Granulated*	11.1	12.2	23.3	193	27.7	332	5.9	2.3	79
Mean	Puddled	19.2	18.2	37.4	260	53.9	444	14.2	4.2	103
	Granulated	18.3	18.6	36.9	251	59.1	465	13.6	4.3	94
	$HSD_{.05}$	5.0	2.7	9.8	69	16.0	136	4.1	22	12
	CV(X)%	15	16	13	14	14	15	15	22	16

* Visual symptoms of extreme P deficiency.

granulated treatments responded rapidly to the N topdressing differentials while no response was observed in the puddled counterparts. The large yield differences were associated with the number of grains per panicle and not with other plant characteristics and yield components. This suggests that N at the panicle-initiation stage was a limiting factor. These results indicate that the efficiency of applied N utilization is lower in granulated soils perhaps because of nitrification-denitrification losses caused by delayed flooding and a possible increase in water movement.

3. *Effects of puddling—water-table interactions on rice growth and nitrogen relations*

In a preliminary trial, redox potential measurements showed that the granulated, −15-cm treatments had an oxidized topsoil over a reduced one, while its puddled counterparts showed a reduced topsoil in spite of not being flooded (Fig. 1).

Maahas soil. No differences in early growth vigor between puddled and granulated treatments were observed in this soil. The puddled-

TABLE 4

Effect of puddled and granulated soil management systems on rice performance and N response under wet season field conditions

Soil Management System	kg N/ha Applied	Grain Yields kg/ha	% N contents			N Uptake (kg N/ha)		
			32[1]	58	120	32	58	120
Puddled	66	4883	4.27	1.68	0.89	32	88	92
	91	4681	—	—	0.69	—	—	66
	116	4541	—	—	0.89	—	—	85
Granulated	66	3511	3.56	1.08	0.76	34	44	58
	91	3979	—	—	0.91	—	—	78
	116	3945	—	—	0.98	—	—	82

[1] Days after seeding corresponding to maximum tillering, panicle initiation, and maturity stages. Topdressing differential established at 60 days.

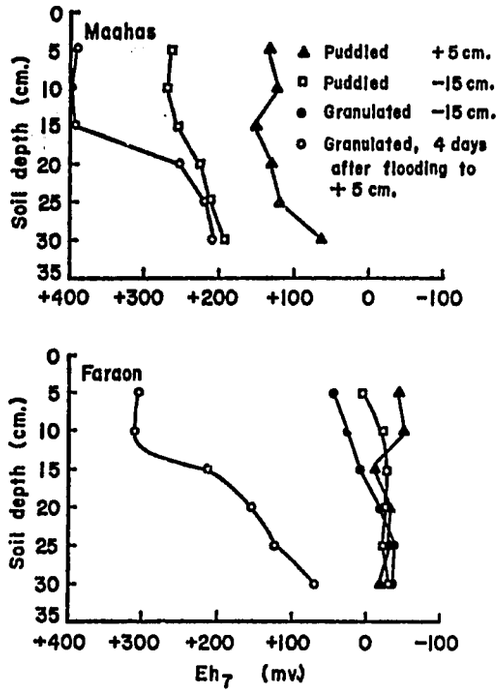

FIG. 1. Redox profile of the treatments in the third experiment.

unflooded treatments showed water stress symptoms apparently caused by restricted root development due to topsoil shrinkage and cracking in spite of daily water additions which kept the water table at about 15 cm below the soil surface. No such stresses developed in the granulated treatments at the same water table level. Nitrogen deficiency symptoms appeared only in the granulated-flooded treatment during the fourth week but were corrected by the topdressing application. Growth rates among all treatments but the puddled-unflooded were very similar (Fig. 2). At harvest, the granulated-unflooded treatment produced identical yields to the flooded-puddled ones but with a significantly higher N uptake (Table 5). All other treatments were superior to the puddled-unflooded one, which showed marked reduction of water use and N uptake.

Faraon soil. The granulated-flooded treatment began to show chlorotic symptoms and stunted growth at 26 days after planting while its puddled counterpart grew normally. The granulated-unflooded treatments also grew slowly at first but later increased its growth rate and approached the puddled-flooded treatment (Fig. 2). The puddled-unflooded treatment also developed water stress symptoms due to soil shrinkage and had slower growth rates. The puddled-flooded treatment significantly outyielded all others at harvest (Table 5). It was followed by the granulated-unflooded and puddled-unflooded treatments and by the granulated-flooded treatment which produced less than half the yield as its puddled counterpart. The granulated-flooded treatment showed throughout its growth a uniform chlorosis coupled with lack of iron coatings on it roots. Iron deficiency in this calcareous soil was suspected but a leaf Fe test did not indicate it.

Nitrogen uptake from soil and fertilizer sources. The results of the N^{15} analysis at three growth stages appear in Fig. 3. The uptake of native soil N with time was almost identical in both Maahas flooded treatments. However, at 30 days after planting when previous beneficial effects of puddling were observed, the percentage of tissue N derived from soil N was 26 percent when puddled and 53 percent when granulated. At harvest, there was little difference (39 vs 36 percent). Under these conditions, therefore, puddling did not increase the utilization of native soil N. Figure 3 shows that the uptake of fertilizer N was higher in the puddled-flooded than in the granulated-flooded treatments. Differences in the percentage of fertilizer recovery at the flowering stage were large (38 vs 27 percent) but decreased at harvest (39 vs 35 percent). Under flooded conditions, therefore, puddling did not increase the uptake of added soil N but increased the efficiency of fertilizer utilization. The extremely poor growth in the Faraon granulated-flooded treatment resulted in a marked decrease of both soil and fertilizer N uptake.

The granulated-unflooded Maahas treatment showed the highest total N and fertilizer N uptake of the entire experiment. It recovered 47 percent of added N at the flowering stage and 41 percent at harvest. It is interesting to note that this unflooded treatment was not only superior to its flooded counterpart in grain yields but also in its efficiency of fertilizer N utilization. The granulated-unflooded Faraon treatment also showed both higher soil and fertilizer N uptake than its flooded counterpart due to the poor growth of the latter.

Among puddled treatments, the restricted

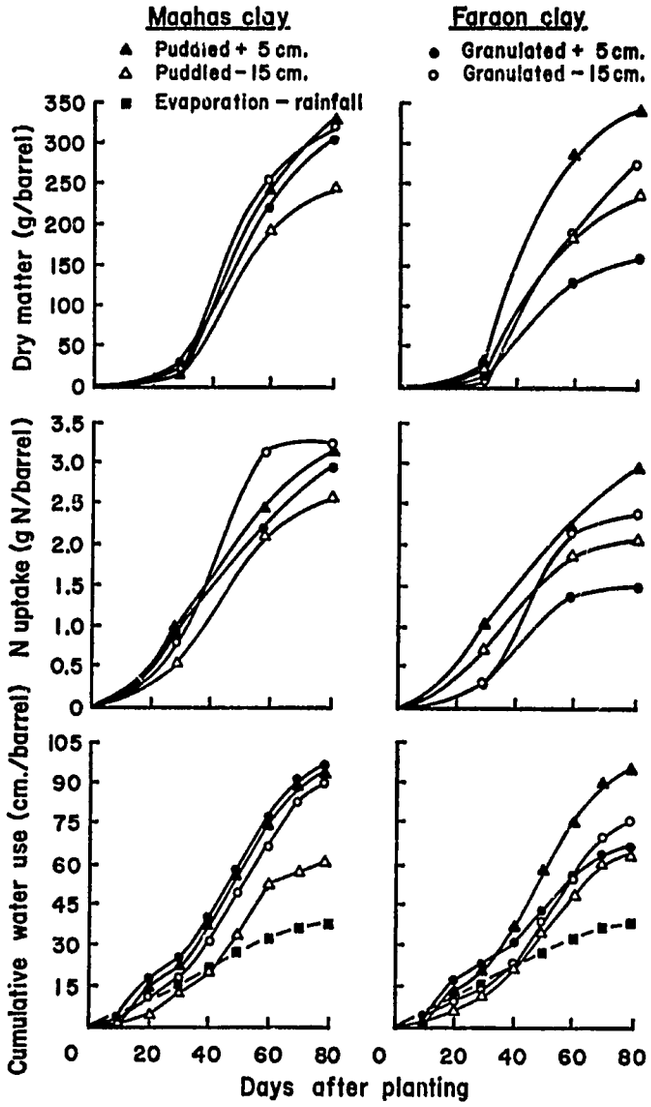

FIG. 2. Effects of puddling and water table levels on growth, N uptake, and water use by rice.

growth associated with irreversible soil shrinkage and cracking resulted in a marked decrease of soil and fertilizer N uptake in both Maahas and Faraon soils. The percentage of fertilizer N recovery values, however, were high and similar to their flooded counterparts. Puddling, therefore, increased the efficiency of fertilizer N utilization under flooded conditions but decreased both soil and fertilizer N uptake when the water table was kept at 15 cm below the soil surface.

DISCUSSION

1. *Nutrient release*

These results show that puddling does not increase the growth and nutrient uptake of rice under flooded conditions with ample N fertilization and in the absence of leaching (Experiment 1) or the uptake of soil nitrogen in the N^{15} study. Superior early growth due to puddling was observed only in the pot experiment but

TABLE 5

Effects of flooding and puddling on rice yields, nitrogen, and water use

Soil	Physical Condition	Water Table (cm)	Grain Yield (g/barrel)	Grain/Straw Ratio	Evapotranspiration (cm H_2O/barrel)	Total N Uptake (g/barrel)	% Recovery of Added N[1]	
							F	M
Maahas	Puddled	+5	185	1.30	93	3.16	32	39
	Puddled	−15	145	1.40	61	2.58	35	42
	Granulated	+5	174	1.34	96	2.96	27	35
	Granulated	−15	185	1.34	89	3.25	47	41
Faraon	Puddled	+5	199	1.41	95	2.94	42	36
	Puddled	−15	142	1.51	63	2.06	39	35
	Granulated	+5	92	1.48	66	1.50	18	19
	Granulated	−15	149	1.47	75	2.36	41	31
	$HSD_{.05}$		13	0.05	4	0.08		
	CV(X)%		7	3	4	8		

[1] F = 50% flowering; M = maturity.

these differences disappeared after the first month of growth. No evidence of increased mineralization of soil organic matter as measured by soil N uptake was observed at any growth stage in the N^{15} trial. These results do not support the theories that puddling increases the soil's nutrient supplying capacity to the rice crop (Grant 1965; Koenigs 1961; Koenigs 1967), particularly of phosphorus, considering the extremely wide range of P availability represented in the soils studied.

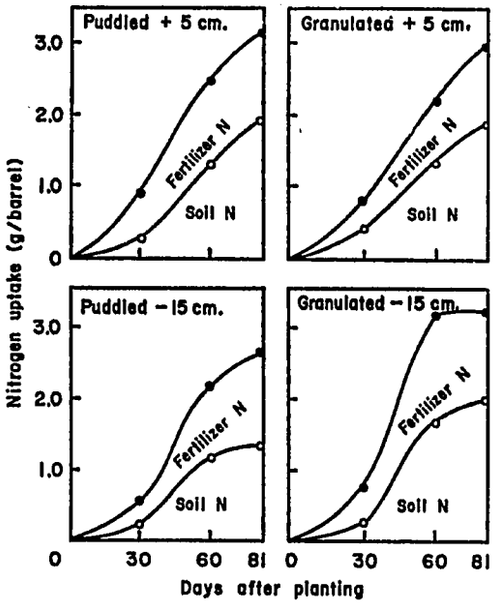

FIG. 3. Effects of puddling and water table levels on the uptake of soil and fertilizer N by rice.

2. *Flooding and nitrogen relations*

Under rainy season field conditions with the subsoil saturated with water, the traditional puddled soil management system was definitely superior to direct seeding on well-granulated soils in which submergence was delayed until 35 days after planting. The data suggest (but do not prove) that the granulated soils may have suffered serious denitrification and N leaching losses at the onset of flooding as well as afterwards due to the observed higher water consumption in the granulated plots. It should be emphasized that the N management practices used in the field experiment were those considered efficient for puddled soils. By delaying the timing of N applications until flooding or by broadcasting pregerminated seeds on previously puddled but flooded soils, the efficiency of applied N may increase sufficiently to offset these differences.

The third experiment proved that rice can perform similarly well in puddled and granulated flooded Maahas clay when the propensity for higher N losses was reduced by equal timing of flooding and no leaching. The almost identical yields observed between puddled-flooded and granulated-unflooded treatments with good N management illustrates the flexibility of the rice

plant in adapting to different levels of soil structure, water management and topsoil redox potentials in a relatively fertile soil like Maahas clay.

Many experiments have shown flooding to be beneficial to rice growth as compared with unflooded treatments kept at field capacity or higher tensions due to increased nutrient availability under reduced conditions (Clark, Nearpass, and Sprecht 1957; International Rice Research Institute 1963, 1965, 1966; Shapiro 1958; Tanaka, Nojima, and Uemura 1965) or water stress elimination (Basak 1957; International Rice Institute 1965; Iyama and Murata 1961; Minabe 1962). In the granulated-unflooded treatment, the low soil moisture tensions in the A horizon prevented water stress and the rice roots could grow in both the oxidized topsoil and the reduced subsoil. Under field conditions, a water table at about this level might be difficult to maintain, but in the subsoil saturated with water the use of raised beds of well-granulated soils where direct-seeded rice could be planted may approximate this situation as shown by Bradfield (1969).

The poor rice growth on the calcareous Faraon soil under granulated-flooded conditions is not adequately explained by the data. Since the granulated-flooded treatment was inferior to the granulated-unflooded counterpart, some detrimental effect of flooding may have taken place. The absence of a similar effect in the puddled flooded soil may have been due to the fact that the topsoil reduction process started with the puddling operation at 9 days *before* planting as compared with 14 days *after* planting in the granulated treatments. If toxic peaks of reduction occurred, they must have taken place prior or shortly after seeding in the puddled treatment and not until 20 to 30 days after planting as in the granulated treatment. Such timing differences have been shown to be very significant to rice growth in soils with high capacity to produce CO_2 (International Rice Research Institute 1966). These assumptions were not tested; if, however, they are true, then the differences in growth between the flooded puddled and granulated Faraon soils are due to indirect effects of puddling such as the time at which the soil reduction process started.

It should be noted that these rice performance comparisons were conducted on representative Philippine lowland rice soils which are not highly weathered. The effects of puddling on highly weathered soils may be different.

SUMMARY AND CONCLUSIONS

Puddling representative Philippine lowland rice soils did not increase rice growth and soil nutrient uptake under conditions of restricted or no leaching. Puddling decreased losses of applied N in field and barrel conditions, which resulted in higher yields in the field. A well-granulated soil performed as well as a flooded puddled one whether it was flooded or had a water table kept at the A-B horizon interphase. The advantages of puddling tropical rice soils do not seem related to increases in nutrient availability but, rather, to indirect effects of water relations.

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SOIL SCIENCE
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Vol. 115, No. 4
Printed in U.S.A.

PUDDLING TROPICAL RICE SOILS: 2. EFFECTS OF WATER LOSSES[1]

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Received for publication April 7, 1971

The work described in the previous paper of this series indicated that the benefits of puddling tropical rice soils were not related to increases in soil nutrient uptake, and that the superior behavior of rice under puddled field conditions was associated with lower N losses caused by restricted water movement (Sanchez 1973). The same investigation suggested that puddled but unflooded topsoils may restrict root development and yields when irreversible shrinking and cracking occurs, while in well-granulated soils such conditions do not take place. More than 75 per cent of Southeast Asia's puddled rice areas depend exclusively on rainfall for their water supply during the monsoon season (Barker 1970). Periodic droughts commonly occur during this period which can cause water stress to the rice crop (Yñiguez and Sandoval 1966). The purpose of this study was to quantify some of the aspects of water relations in puddled soils in order to provide a more accurate picture of the advantages and limitations of puddling tropical rice soils.

EXPERIMENTAL

1. *Effects of temporary drought in rainfed puddled fields*

Two rainfed puddled rice fields of Maahas clay adjacent to those previously described (Sanchez 1973) were compared with a flooded puddled field during the Philippine rainy season. Replicated observations were made in the following fields in areas ranging from 400 to 600 m^2. Field I was kept constantly flooded by irrigation. Field II was rainfed. Heavy rainfall kept it flooded or saturated during the first 60 days after transplanting. A two-week rainless period followed which caused cracking and shrinkage. Subsequent rainfall kept this field saturated with water during the rest of crop growth. Field III was also rainfed. It remained flooded during the first month after transplanting, but cracked and shrank after a period of two weeks. This field suffered from alternate flooding and drying during the rest of crop growth. The IR8 rice variety was transplanted uniformly in a similar way as reported previously. Nitrogen was incorporated at the rate of 91 kg N/ha prior to transplanting. Plant characteristics and yield components were measured at several growth stages. Root development was visually examined at harvest.

2. *Water loss pattern in puddled and granulated soils*

The following trial was designed to quantify the effects of puddling on downward water movement. A pot experiment was conducted in an outdoor screenhouse with six rice soils and two soil physical condition levels arranged in a split plot design with four replications. The soils varied widely in clay contents and other properties (Table 1). The Sariaya and Pila soils are developed from young alluvium. Among the clayey soils, Buenavista and Lipa are predominantly montmorillonitic (Galvez 1957), Antipolo is kaolinitic (Galvez, Briones, and Veracion 1964) and Isarog is probably allophanic.

The 5-liter clay pots were painted with coal tar and provided with a glass wool filter at the bottom. The filters were calibrated to produce a flow of 1000 cc/min in all pots when filled with

[1] Agronomy paper No. 977. Contribution of the Agronomy Department, Cornell University. Based on a portion of the author's dissertation under the auspices of the University of the Philippines–Cornell University Graduate Education Program sponsored by the Ford Foundation. The author is grateful to Dr. Richard Bradfield, International Rice Research Institute, for his supervision.

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TABLE 1

Characteristics of the soils used in the water losses experiment

Soil type	% Clay	% Sand	% Silt	% H_2O at W.H.C.*	% H_2O at M.E.*	pH	% O.M.*	C.E.C. (me/100 g soil)	Exch. Ca (me/100 g soil)	Exch. Mg (me/100 g soil)	Exch. K (me/100 g soil)
Sariaya sandy loam	9	71	19	45	18	5.9	2.27	10.33	5.10	1.83	0.72
Pila sandy clay loam	24	50	26	74	31	6.5	2.00	22.16	13.09	6.99	0.64
Buenavista clay loam	30	40	30	76	30	5.7	1.07	24.24	18.72	3.79	1.05
Lipa silty clay	40	15	44	95	40	5.8	2.14	32.13	16.45	6.99	1.79
Antipolo clay	64	9	27	87	40	4.7	2.45	22.11	6.80	4.56	0.40
Isarog silty clay	46	13	41	90	48	4.9	8.69	34.41	7.51	2.60	1.12

* W.H.C.: Water-holding capacity; M.E.: Moisture equivalent; O.M.: Organic matter.

TABLE 2

Effects of water status of rainfed puddled and irrigated fields on IR8 rice during the wet season

Field No.	Grain Yields (kg/ha)	Root Development Depth (cm)	Root Fe Coatings	Plant Height (cm)	Panicles per m^2	Grains per Panicle	100 Grain Weight (g)	% Sterile Grains
I	3923	15–20	yes	113	214	132	2.84	16
II	4831	15–20	yes	96	248	138	2.78	35
III	1808	2–4	no	79	188	101	2.32	47

water. The equivalent of 4 kg of oven-dry soil was subjected to several wetting and drying cycles until the best degree of granulation was attained. After filling in the pots, they were slowly wetted to saturation from the bottom and the moisture content at visual saturation recorded. Three hand puddling operations were conducted until aggregate destruction was virtually complete. After six days of settling, soil moisture contents were adjusted to saturation and the water table was raised to 1 cm above the soil surface. The filters were opened and percolates were collected in bottles during seven days. Total water losses were determined by weighing the previously tared pots. Evaporation losses were calculated from the differences. Rainless sunny days with a solar radiation average of 436 g-cal/cm^2/day characterized the weather during this period.

3. *Field behavior of granulated systems in wet and dry seasons*

Two trials conducted during the rainy and dry seasons compared the growth of direct-seeded IR8 rice on granulated soils at two subsoil water-table levels. The experiments were located in adjacent 2500-m^2 plots on Maahas clay soil. Land preparation, seeding, and other cultural practices were similar to those reported previously (Sanchez 1973). The water-table level during the wet season fluctuated at about the subsoil-topsoil interphase, but remained at about 100 cm below the soil surface during the dry season. The blocks were divided into several nitrogen management treatments and their replications. Flooding was attempted in both cases at approximately one month after seeding.

RESULTS AND DISCUSSION

1. *Effects of temporary droughts on rainfed puddled fields*

Top and root development in the rainfed Field II were similar to the constantly flooded Field I in spite of topsoil drying and cracking at 60 days after transplanting (Table 2). The effects of topsoil drying and cracking at 30 days after transplanting in Field III were extremely detrimental. Root penetration below the top 2–4 cm was negligible and no Fe root coatings indicative of soil reduction were visible at harvest time. Field III yielded about one-third of Fields I and II. These lower yields are associated with decreases in plant height and yield components appearing in Table 2. The data indicate that

rainfed puddled soils may shrink and crack irreversibly during crop growth and that the time at which this may happen can impede root development and drastically affect rice production.

These results indicate that the stage of plant development at which the Maahas puddled soil changed from a soft consistency into hard cracked massive clods, seriously affects rice performance. When such change took place during the first month of growth, yields decreased to about one-third of that obtained when shrinking took place a month later. The data confirm previous experimental observations (Sanchez 1973) that soil shrinkage and swelling can reduce yields and N uptake of rice in a puddled soil with a water table kept at 15 cm below the soil surface, while excellent growth took place in well-granulated soils at the same water-table level. These plant performance differences are intimately associated with the formation of a physical barrier to root development which was irreversible during the rice growing season. Puddling, however, is not an irreversible process, but thorough drying of the soil is prerequisite for structural regeneration (McGeorge 1937).

2. Water loss patterns in puddled and granulated soils

Soil moisture depletion patterns (Fig. 1) indicate that water was quickly lost in granulated soils within one hour. Afterwards, the loss pattern was essentially parallel between puddled and granulated soils, the latter averaging about 20 per cent lower water contents. The initial losses, ranging from 570 to 975 cc/pot represent percolation in granulated soils. Very small but detectable percolation losses were observed in the finer textured Buenavista, Lipa, and Antipolo puddled soils, while larger amounts of 285, 230, and 280 cc/pot were registered in the coarser textured Sariaya and Pila soils and the Isarog volcanic ash soil (Fig. 2). The larger particle size of the sandy loam apparently diminished the effects of puddling. The volcanic ash soil, although a silty clay by mechanical analysis, behaved similarly to the sandy clay loam in its percolation losses in the puddled state (Fig. 2), but approached the heavier clays in its water retention (Fig. 1). The remarkable physical properties of these soils have been attributed to

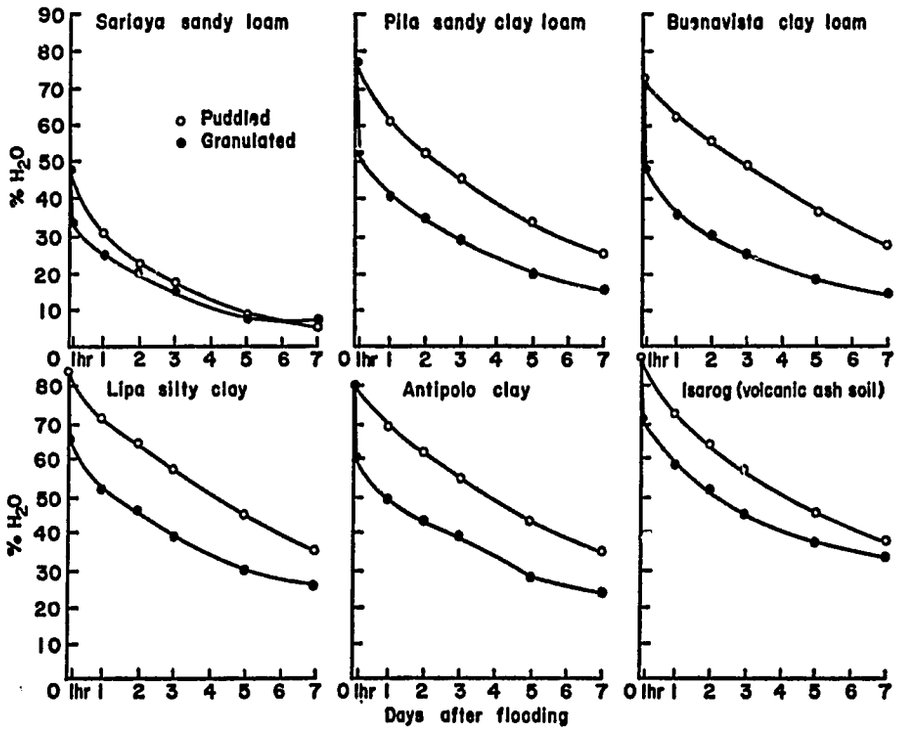

Fig. 1. Soil moisture depletion patterns in puddled and granulated soils.

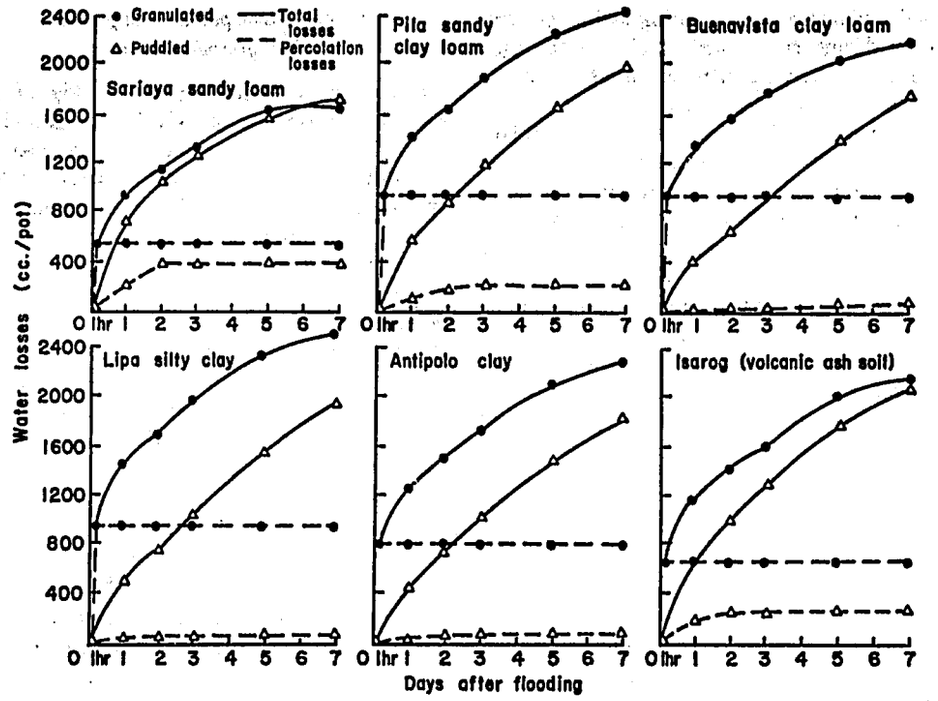

FIG. 2. Cumulative water losses through percolation and evaporation in puddled and granulated soils.

the intimate mixture of its high organic matter contents with allophane (Wright 1964).

The dramatic differences in percolation losses between puddled and granulated soils (Fig. 2) show that granulated soils lost approximately one-third of the water by percolation and two-thirds by evaporation in seven days. The puddled soils on the average lost one-tenth by percolation and nine-tenths by evaporation during this trial. Drainage rates, calculated by the amount of percolate collected until the flow became less than 10 cc/day (from 7 to 20 min in the granulated treatment and from 48 and 120 hr in the puddled ones) appear in Table 3. Puddled treatments averaged 1.8 mm/day with a range from 0.5 to 4.5. Granulated treatments averaged 2169 mm/day with a range from 1545 to 2684. Drainage through a puddled soil was about 1000 times slower than through well-granulated soils in pot conditions. Granulated:puddled drainage ratios averaged 1204 and ranged from 593 in the sandy loam to 5367 in the montmorrillonitic silty clay.

The nature of the water losses trial differs from ordinary laboratory percolation rate experiments in that no constant head of water was maintained since its purpose was to measure

TABLE 3

Effects of puddling on rates of drainage in six soils. (All soils were flooded with a head of 1 cm at the start.)

Soil Type	% Clay	Drainage Rate (mm H_2O/day)	
		Granulated	Puddled
Sariaya sandy loam	9	2670	4.5
Pila sandy clay loam	24	2147	1.7
Buenavista clay loam	30	1827	0.5
Lipa silty clay	40	2684	0.5
Antipolo clay	64	1546	0.5
Isarog (volcanic ash soil)	46	2139	3.1
Mean of soils		2169	1.8

$HSD_{.05}$ (soils): 515
$HSD_{.05}$ (physical condition): 162
$HSD_{.05}$ (S × P): 475
CV(X): 14%

water loss patterns. Hence the term "drainage rate" is used. The drainage rate values obtained for puddled soils are of the same order of magnitude as measurements of deep percolation rates in field observations. For example, an average value of 0.5 mm/day has been reported for puddled Maahas clay fields (International Rice Research Institute 1963), which is identical to the drainage rate of Lipa silty clay, its better-drained associate. The higher values obtained in the puddled volcanic ash soil and the sandy loam (3.5 and 4.5 mm/day, respectively) reflect the percolation loss problems of puddled soils of a similar nature in Japan (Matsubayashi et al. 1967). Under field conditions, the subsoil water table level will severely affect these differences. The granulated treatments probably were more loosely packed in these pots than under field conditions, which may have exaggerated somewhat these differences. Nevertheless, it is obvious that water movement through well-granulated and puddled soils, regardless of texture, is several orders of magnitude different.

This experiment further indicates that puddling per se drastically reduces water losses in rice soils, a reasoning which has been attributed to the "plow pan" formation (Sanchez 1973). The literature has shown that "plow pans" are limited to specific soil types, while puddling is almost universal in lowland rice farms in Tropical Asia. With the dikes surrounding the paddy fields and the puddled soil at the bottom, the traditional rice farmer holds as much water as he can to grow rainfed rice crops during the rainy season.

3. Field behavior of granulated systems in wet and dry seasons

The wet season experiment remained flooded by rains or irrigation. The dry season experiment could not be permanently flooded and suffered from severe N leaching losses which essentially eliminated nitrogen rate and timing differentials. Water was lost in this unpuddled soil through very fast lateral water movement into unflooded adjacent areas. Average crop results appear in Table 4, which shows that the very low yields of IR8 during the dry season crop were associated with a high proportion of ineffective tillers, lower grain: straw ratios, number of grains per panicle, and 100 grain weights over the wet season crop, indicating that the crop was severely affected by water and N leaching losses at several growth stages.

TABLE 4

Comparison of plant characteristics and yield components of IR8 grown in wet and dry seasons under granulated soil conditions

Season	Grain Yields (*kg/ha*)	Plant Height (*cm*)	Panicles per m^2	% Effec. Tillers	Grain: Straw Ratio	Grains per Panicle	100 Grain Weight (*g*)
Wet	5015	97	230	89	1.15	125	2.94
Dry	2693	79	218	49	0.63	78	2.47

The field experiment and more recent observations (Bradfield 1969) indicate that rice can perform well under granulated soil conditions during the rainy season when the subsoil is saturated with water and N leaching losses are minimized by proper management. When the water table is near the surface, water movement will be mainly in the form of saturated flow. Then the differences between puddled and granulated conditions may be minimized. The dry season experiment demonstrated that when the water table was deep, growing rice on well-granulated Maahas clay resulted in excessive water and N leaching losses and poor yields.

The slow water-loss pattern of puddled soils which is so advantageous to rice growing, seriously limits the potential of multiple cropping proposed by Bradfield (1969). Puddling seriously delays the time at which the soil may dry out enough to regenerate its former structure by alternate wetting and drying. After the rainy season field experiments, a series of crops such as sweet potatoes, soybeans, and sorghum were planted within two weeks after the rice harvest in the granulated plots, while a worthless combination of ratoon rice and weeds grew in the puddled treatment for four months until the soil was dry enough to be subjected to structural regeneration.

CONCLUSIONS

The two papers of this series show that the advantages of puddling some tropical rice soils are directly or indirectly related with decreasing water losses and not with increasing nutrient-supplying capacity. In all experiments, puddled

flooded treatments produced similar or higher rice yields than other combinations.

The limitations of puddling rice soils are in restricting root development when the soil shrinks and cracks at early stages of rice growth in rainfed systems and the slow water-loss patterns after rice harvest which might limit rotations with other crops.

When excessive water movement is not a limiting factor, excellent rice performance can be obtained from well-granulated soils.

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