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Experience with Soil Taxonomy of the United States—*Marlin G. Cline*

Agrotechnology Transfer in the Tropics Based on Soil Taxonomy—*F. H. Beinroth, G. Uehara, J. A. Silva, R. W. Arnold, and F. B. Cady*

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Agrotechnology Transfer in the Tropics Based on Soil Taxonomy–
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Preface

Agrotechnology transfer among countries can only be successful if all participants are aware of developments innovations, and possibilities in their fields. This is often done through distribution of publications that are considered to be valuable pieces of information. This reprint of articles from a recent issue of *Advances in Agronomy* is one service from the Soil Management Support Services of the Soil Conservation Service, in collaboration with the Benchmark Soils Project, University of Hawaii. Both projects are supported by the Agency for International Development (AID).

The SMSS (Soil Management Support Services) was initiated in 1979 to assist developing countries in soil survey, classification, interpretation, and management of their resources. The program also provides technical assistance to AID missions in developing countries and cooperates with other international organizations. The BSP (Benchmark Soils Project) began in 1974 to test the hypothesis of agrotechnology transfer based on the soil family classification of Soil Taxonomy. Based at the Universities of Hawaii and Puerto Rico, the Project has 25 experimental sites in Brazil, Cameroon, Hawaii, Indonesia, the Philippines, and Puerto Rico.

Cline's article examines the impact of Soil Taxonomy since its publication in 1975. Based on a questionnaire he sent to many cooperators throughout the world, he reviews the use and application of the system and concludes that "the impact of Soil Taxonomy on soil classification worldwide has been far greater than that of any other development in the discipline during the past 50 years."

Beinroth et al. examine and develop the prerequisites for worldwide agrotechnology transfer using Soil Taxonomy as the vehicle. The paper also gives the underlying concepts of the Benchmark Soils Project, which was designed to assist developing countries to bypass the three major constraints for better utilization of land resources—lack of trained personnel, lack of capital, and, more specifically, lack of time to solve their immediate needs.

Through these reprints we hope to open a dialogue with all soil scientists, and we welcome your suggestions and comments.

—**Hari Eswaran**
Program Leader,
Soil Management Support Services

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EXPERIENCE WITH SOIL TAXONOMY OF THE UNITED STATES[1]

Marlin G. Cline

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I. INTRODUCTION

Readers should recognize that much of the literature cited in this article is based on an incomplete preliminary draft of Soil Taxonomy, known widely as "The Seventh Approximation" (Soil Survey Staff, 1960), and on four supplements issued in 1964, 1966, 1967, and 1968. During the 15 years from release of

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the Seventh Approximation until the complete text was published for general distribution (Soil Survey Staff, 1975), the number of great groups recognized in the system increased from 112 to 230, and the number of subgroups, from 281 to 1251. The basic concepts and principles, however, changed much less. The National Cooperative Soil Survey of the United States has used the system as its official taxonomic classification since January 1965. The date of an article cited may be used as an approximate indicator of the stage of development of the system on which it is based. The author has been selective to avoid citing conclusions that would have been clearly outdated by subsequent changes in the system.

To bring the information available up to date, the author requested leading soil scientists of 46 countries to respond to specific questions about use of the system in the areas they represent, including (1) how much and in what ways it is used; (2) problems encountered in the mechanics of its application; (3) problems of classifying soils by its criteria; (4) its impact on soil surveys; and (5) its usefulness for development of soil interpretations for applied purposes. Fifty-three individuals, representing 31 foreign countries, responded. Four others responded for multicountry areas. Sixteen responded for five agencies of the United States. The individuals are identified by the countries or areas they represent in footnote 2. Information from these sources is identified in the text as "personal communication" by the convention (PC) and is cited in the present tense to distinguish it from that derived from published literature.[2]

[2]The author is most grateful to the individuals named below for invaluable assistance. All responded to the author's request for information, either by answering specific questions or by referring the inquiry to others. Many added relevant comments or supplied documents that would not otherwise have been seen. For foreign countries: Argentina—C. D. Scoppa; Australia—K. H. Northcote and R. F. Isbell; Belgium—R. Langohr; Brazil—M. Camargo; Canada—G. M. Coen, L. M. Lavkulich, W. W. Pettapiece, I. Snedden, and C. Tarnocai; Chile—M. Carrasco, J. Munito, W. Luzio, and J. Salgado; Colombia—R. Guerrero; Costa Rica—A. Alvarado; England and Wales—B. W. Avery, P. Bullock, and B. Clayden; Federal Republic of Germany—E. Mueckenhausen; Hungary—L. Szabolcs; India—S. B. Deshpande, R. S. Murthy, and S. S. K. Nanda; Iraq—F. H. Altaie; Ireland—T. Walsh and M. Gardiner; Japan—M. Oyama; Kenya—F. N. Muchena and P. M. Ahn; Netherlands—J. Schelling and W. G. Sombroek; New Zealand—B. C. Barrat, E. Griffiths, M. L. Leamy, and W. C. Rijkse; Norway—J. Lag; Pakistan—M. B. Choudhri; Peoples Republic of China—Lien-Chieh Li; Romania—A. Canarache and C. Rauta; Scotland—J. M. Ragg; South Africa—C. N. MacVicar and M. C. Laker; Sri Lanka—K. A. De Alwis and R. Tinsley; Sudan—M. A. Ali; Thailand—S. Panichapong; Trinidad—N. Ahmad; USSR—I. P. Gerasimov; Venezuela—J. Comerma; Zimbabwe Rhodesia—J. M. DeVillers and W. D. Purves. For the United States: Soil Conservation Service—K. W. Flach, R. L. Guthrie, J. E. McClelland, M. Stout, J. M. Williams, and J. E. Witty; Forest Service—R. G. Cline, D. Eagleston, M. Kaplan, R. Poff, W. Sexton, A. Sherrell, and G. Warrington; Iowa—T. E. Fenton; North Carolina—S. W. Buol; Texas—L. P. Wilding. For multicountry areas: G. D. Smith, general perspective; C. Charreau, French-speaking Africa; F. Moorman, Africa and Southeast Asia; S. W. Buol, Latin America; W. B. Peters, World Bank. Citations of the personal communications from these individuals are identified in the text by (PC).

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II. GENERAL REACTIONS TO THE SYSTEM

General reactions to Soil Taxonomy in the literature have ranged from absolute rejection to substantial endorsement, each in the context of the author's precepts of principles of classification and of order in relationships among soils. Some of the literature cited here illustrates an observation by Mulcahy and Humphries (1967) that "It is the subjective, and therefore, emotionally involved nature of most soil classifications which turns the scientist from the narrow path of detached reason."

The extremely negative reaction of Russian soil science is not easily rationalized. Gerasimov's (1962) initial review was a critical but reasoned statement. He noted some merits of the Seventh Approximation and was critical of several of its attributes, including his interpretation that it had abandoned the principles of Dokuchaiev. In 1964, a series of 11 articles in *Pochvovedenie* (No. 4, pp. 14–48) found little merit in the system's logic or in its applications to soil classification of specific areas, to soil genesis, to soil survey, or to soil geography. A translation of the summary paper (Gerasimov, 1964) characterized the system as an empirical scheme "justified by references to the most widespread modern bourgeois-philosophical, subjective-idealistic trends" and of "limited positive interest." Later reviews have been similarly critical (Gerasimov, 1969, 1978).

Soil Taxonomy is a major departure from the philosophy of classification followed by the Russian school. D'Hoore (1968) noted that Russian soil classification relies heavily on factors of soil formation as criteria of the higher categories. Soil Taxonomy uses intrinsic soil properties selected with the effects of soil formation as criteria, but Yerokhina and Sokolova (1964) appear to consider this a violation of Dokuchaiev's principles. Fridland (1964) denied that soil classifications are not truth but are contrivances to suit people's purposes, as declared by the authors of Soil Taxonomy, apparently accepting genetic theory as truth in detail. These kinds of differences and the fact that translations of English to Russian may not convey the bases of Soil Taxonomy fully could account for parts of the critical reviews, but they do not explain them fully.

Muir (1962) was critical of the Seventh Approximation, largely on grounds that it provided no statement of basic principles as he conceived them. Webster (1968a) found the strictly defined limits of the criteria of the Seventh Approximation unjustified in view of errors of their measurement and, like Avery (1968), maintained that a hierarchal system is not appropriate for soils. He found no relevance in the concepts of pedon and soil individual (polypedon) and concluded that the system exhibits circular reasoning. Mitchell (1973) published a rebuttal to both Webster and Avery, questioning the validity of their analyses. Webster (1968b) also discussed faults of the system for use by geographers and advised them to avoid using it. Bunting (1969) promptly published a note in the same

journal characterizing Webster's review as most subjective and unjust. These are examples of diametrically opposing viewpoints related to concepts and biases of individuals.

Australian soil scientists generally have been critical of Soil Taxonomy, though judgments have varied among individuals. A committee of the Australian Society of Soil Science reviewed the Seventh Approximation in detail. They reported it a great improvement over earlier schemes but with serious problems for soils of Australia (Butler *et al.*, 1961). Stephens (1963) took exception to a number of assumptions, criteria, and definitions and considered the system more nearly a key than a classification. He too found serious deficiencies for soils of Australia. At a time when factual keys were gaining acceptance in Australia, Mulcahy and Humphries (1967) reported that the Seventh Approximation was an entirely commendable attempt to maximize information content but that the use of criteria reflecting soil genesis was logically indefensible. They characterized the choice and weighting of criteria as subjective and so biased by conditions in the United States that application in Australia was not satisfactory. Currently, Northcote (PC) reports that few Australian soil scientists are inclined to devote time to use of Soil Taxonomy. In contrast, Moore (1978) has concluded that Soil Taxonomy has good potential as a medium for transfer of technology in Australia.

MacVicar *et al.* (1977) have not been completely satisfied with the results of application of Soil Taxonomy in South Africa. They commented, however, that the system is "refreshing" and has "loosened the shackles of traditionalism and stimulated rethinking on soil classification." Laker (PC) writes that the system has had a revolutionary impact on ideas about soil classification and soil survey in South Africa, although it is not used as a national system.

Sehgal and Sys (1970) found a need for changes in detail of some criteria to accommodate important properties of soils of the Punjab. They emphasized, however, that criticism based on departure from theories of soil genesis is invalid and that genetic relationships are shown more specifically than ever before. They noted the lack of geographic bias for Entisols, Vertisols, Histosols, and Inceptisols but commended the strengthening of relationships between soil classification and soil geography through the concepts of the pedon and polypedon.

Langhor (PC) disagrees with ideas expressed in Soil Taxonomy about genesis of fragipans and argillic horizons, which influence choice and weighting of criteria strongly. He would construct some parts of the system differently. Nevertheless, he considers it the most precise and best system for international communication though not well suited to definition of mapping units in the soil survey of Belgium. Like many others, he deplores the complicated writing of the published system.

One of the most objective and comprehensive studies of the system has been reported by Ragg and Clayden (1973). They concluded that use of quantitative

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criteria, the concept of diagnostic horizons, emphasis on criteria not readily altered by man, and the nomenclature are valuable contributions. They saw great value in the system as a medium for international reference but found problems for its application in Britain. They identified the complexity created by large numbers of taxa above soil families, the complexity of definitions, emphasis on the mollic epipedon and base status as criteria, and need to amend definitions of some criteria as deficiencies for classification of British soils. They concluded, however, that the system had brought traditional British groupings rightfully into question and had placed soil classification on a more acceptable scientific level.

Leahey (1963) reported that Canadians were greatly impressed by the Seventh Approximation but for national purposes preferred to continue with the system they were constructing. The two systems have been developed concurrently with considerable interaction and commonality of language and structure. Coen (PC) writes that many, if not most, criteria of the Canadian system (Clayton *et al.*, 1977) have been strongly influenced by Soil Taxonomy; some are identical. It should also be noted that Canadians have contributed to Soil Taxonomy.

Rauta (PC) reports that although Romania uses its own classification, Soil Taxonomy is respected as a secondary system. He cites its use of intrinsic soil properties, quantitative diagnostic criteria, and connotative nomenclature as important attributes. He is critical of the use of the same properties as diagnostic criteria at different levels in the system and of the complexity of both definitions and their presentation. Some Romanian soil scientists have contributed to Soil Taxonomy and take special interest in it.

Duchaufour (1963) noted deficiencies of the Seventh Approximation for use in France but considered it a mark of real progress in soil classification. Kesseba *et al.* (1972) found it the most comprehensive framework for assessing Tanzanian soil resources even though it did not fit well everywhere.

Conflicting viewpoints involving national pride are revealed by a resolution of the New Zealand Society of Soil Science requesting reconsideration of a decision by the Soil Bureau to use Soil Taxonomy on a trial basis. Miller (1978) provided a concise review of experience in New Zealand, the level of interest in Soil Taxonomy, and reasons for experimenting with it.

III. USE OF SOIL TAXONOMY INTERNATIONALLY

Table I summarizes the predominant intensity and frequency of use of Soil Taxonomy by scientists of the major institutions concerned with soils in countries for which information is available. Scientists of most countries that are not listed probably use the system infrequently if at all.

Table I
The Intensity and Frequency of Use of Soil Taxonomy by Country[a]

Used continually as a primary system	Used frequently as a secondary system	Used infrequently or not used
Argentina	Belgium	Australia
Chile	Bolivia[b]	China, Peoples Republic
Colombia	Brazil	France[d]
Ecuador[b]	Canada	Germany, Federal Republic
Guyana[c]	Costa Rica	Guatemala[c]
India	England and Wales	Haiti[c]
Iraq	Ghana[d]	Hungary
New Zealand	Iran[d]	Mali[e]
Pakistan	Ireland	Mauritania[e]
Sudan	Japan	Mexico[c]
United States	Kenya	Netherlands
Venezuela	Nigeria[d]	Niger[e]
	Peru[b]	Norway
	Romania	Panama[c]
	Sierra Leone[d]	Scotland
	Sri Lanka	Senegal[e]
	Thailand	South Africa
	Tanzania[d]	Upper Volta[e]
	Trinidad	USSR
		Zimbabwe Rhodesia

[a] Based on personal communication with scientists in the countries, except as noted.
[b] Information provided by S. Buol, North Carolina State University.
[c] From an unpublished survey of "Soil Taxonomy in the Tropics" by R. Guerrero, University of Puerto Rico.
[d] Based on evidence in the literature.
[e] Information provided by C. Charreau, ICRISAT, Dakar, Senegal.

A. Countries Where Soil Taxonomy Is Used as a Primary System

Soil Taxonomy has been used as the official taxonomic system of the National Cooperative Soil Survey of the United States since January 1965. The United States Forest Service also uses the system for taxonomic classification of soils, although their mapping units are identified in other terms for in-service use in some parts of the country. The system is taught in soils courses of major universities. Soils are identified in terms of its taxa in most articles concerned with pedology in the major journals and bulletins of the United States.

Guerrero reports (in an unpublished survey of Soil Taxonomy in the Tropics) that four Latin American countries in addition to the six listed in Table I used Soil

Taxonomy exclusively in their national soil survey operations, but he did not identify them. He reports that Guyana is currently converting from the 1938 USDA system to Soil Taxonomy. C. Scoppa (PC) reports that soil series and their phases are used for soil mapping at scales larger than 1:100,000 in Argentina; subgroups and families are used at smaller scales. Westin (1963) and Comerma (1971) have discussed the advantages of the Seventh Approximation for soil surveys in Venezuela; Comerma also identified some problems that were encountered in its application.

Murthy (PC) reports that 700 copies of an Indian edition of Soil Taxonomy have been distributed and that short courses and regional workshops are being conducted to facilitate its use. In spite of some problems associated with an inadequate data base, Murthy *et al.* (1977) have identified major advantages of the system for India. Articles by Deshpande *et al.* (1971) and Murthy (1979) provide examples of its use.

M. B. Choudhri (PC) reports that Soil Taxonomy is used as a primary taxonomic system for soil surveys of Pakistan in conjunction with FAO units (FAO-UNESCO, 1974). Ahmad *et al.* (1977) identified soils of the Pakistan Punjab by taxa of Soil Taxonomy without comment. The initial steps of converting from a national soil classification for Iraq to Soil Taxonomy have been described by Altaie *et al.* (1969).

Cook (1975) found Soil Taxonomy generally applicable to soils of the Sudan. He reported problems related mainly to deficiencies of information and training of personnel, but he noted that reasonable approximations of classification by the system can be made even though data necessary for precision are lacking. M. A. Ali (PC) reports that the Seventh Approximation was introduced in the Sudan in the 1960s during development of the Soil Survey Administration under FAO auspices. The soil survey of the Sudan is currently correlating taxa of Soil Taxonomy with units of the FAO/UNESCO legend, as is done in Pakistan. Some problems have been encountered with criteria of Vertisols (Ali, 1972). Ali (PC) also reports that the legend for the soil map of Arab countries is based on subgroups of Soil Taxonomy.

The Soil Bureau of New Zealand adopted Soil Taxonomy in 1977 for an extended trial (Miller, 1978). A final decision on its continued use depends on results of that trial.

Some individuals in most of the countries that use Soil Taxonomy as a primary system for soil surveys still prefer other schemes. Individuals contacted by the author in Chile, India, and New Zealand indicate that they use Soil Taxonomy mainly as a secondary system for communication. Guerrero's unpublished survey, cited above, showed that teaching of Soil Taxonomy in universities of many Latin American countries is weak and that a significant number of individuals still rely mainly on systems that were used previously. Guerrero notes in his report that use of these systems is decreasing as workers gain experience with Soil Taxonomy.

B. Countries Where Soil Taxonomy Is Used as a Secondary System

In the 19 countries listed in the second column of Table I, national soils programs depend on taxonomies designed for their conditions or on more comprehensive schemes, such as the FAO/UNESCO legend, the French system, or the 1938 USDA classification. Soil scientists of these countries, however, commonly use Soil Taxonomy for international communication and for correlation of their soils with those of other countries. Butler *et al.* (1961), Deckers (1966), Ragg and Clayden (1973), Beinroth (1975), and Moore (1978) recommended its use for these purposes because of its precision and comprehensive scope, though they preferred other schemes for national purposes. C. Rauta (PC) reports that Soil Taxonomy is not used in Romania for national programs of soil survey and classification but is used frequently in scientific papers, reports for both national and international meetings and symposia, guidebooks, manuals, and Ph.D. theses. De Coninck *et al.* (1976), for example, identified the soils in terms of Soil Taxonomy for a study of clay mineralogy in Romania.

In some of the countries listed, Soil Taxonomy is used in national programs as a secondary system for people of high technical competence, though a less complex scheme is given preference for general use. Dent and Changprai (1973) outlined Soil Taxonomy as the "primary" system for the country's most competent soil scientists in the Soil Survey Handbook of Thailand, but they retained the national system as a scheme more consistent with the technical competence of most workers. Dewan and Famouri (1964) outlined the Seventh Approximation in their publication on soils of Iran but identified soils of the country in terms of the 1938 USDA classification.

Authors who use Soil Taxonomy as a secondary system use taxa of categorical levels ranging from orders to families, depending on the purpose and scale of the study, the level at which soils can be identified with the data available, and the familiarity of the individual with the system.

Orders, suborders, and great groups are used most commonly for studies involving broad perspective. Harris *et al.* (1971) correlated soil zones of Costa Rica at the order level for a very general picture of the soil geography of that country. Aubert and Tavernier (1972) used suborders and great groups as reference taxa for their small-scale soil map of the humid tropics. Moorman and Van Breemen (1978) used great groups to identify soils of the principal rice-growing areas of the world. Camargo and Falesi (1975) and Zamora (1975) identified large areas of Brazil and Peru, respectively, in terms of great groups for broad perspective. Sanchez and Buol (1974) used Soil Taxonomy for their study of soils of the upper Amazon basin, correlating the taxa with units of both the FAO and Peru systems.

Subgroups are used commonly for geographic studies of intermediate intensity

and scale, as in Dijkerman's (1969) report on soil resources of Sierra Leone. Many authors use subgroups in preference to taxa of lower categories to identify soils used for studies of morphology and genesis. Examples include those by Lepsch *et al.* (1977) in Brazil, Walmsley and Lavkulich (1975) and Hendershot and Lavkulich (1978) in Canada, Ojanuga *et al.* (1976) and Harpstead (1973) in Nigeria, Flores *et al.* (1978) in Peru, and De Alwis and Pluth (1976) in Sri Lanka. Some of these were studies of specific pedons for which data should have been adequate for classification at the family level. Many authors appear to prefer to use subgroups, perhaps because they are taxa of the lowest category in which the criteria have strong genetic bias.

Soil families are identified in some studies involving practical interpretations and transfer of technology. The criteria for distinctions at the family level were selected specifically to enhance interpretive value for applied purposes. Uehara (1978) has described the potential of phases of soil families for transfer of technology internationally. North Carolina State University (Soil Science Department, 1978) has used soil families for quantitative identification of soils at experimental sites in the tropics as a basis for transfer of experimental results. Soil families are also used by some authors to identify soils used in studies of morphology and genesis. Family criteria below the subgroup level may be relevant to such studies, as in those by Snedden *et al.* (1972) and Hakimian (1977).

C. Countries Where Soil Taxonomy Is Used Infrequently

In most of the 20 countries listed for this group in Table I, some individuals have at least studied Soil Taxonomy. Australian soil scientists have studied the system in detail as noted in Section II, but most do not use it. Yet R. F. Isbell (PC) reports that he uses it as a secondary system. Soil Taxonomy is not known generally in the People's Republic of China, but Lien Chieh Li (PC) writes that he has a copy and would welcome assistance in using it. The system is well known by leading soil scientists of France. The new French classification (Fauck *et al.*, 1979) uses some of its principles, concepts, and elements of nomenclature, though the taxa and their organization are markedly different. E. Muckenhausen (PC) writes that the system is used little in the Federal Republic of Germany, though it is well known by some individuals.

Guerrero's unpublished study of Soil Taxonomy in the Tropics reveals that Guatemala and Panama use no taxonomic system and that Mexico and Haiti use other schemes exclusively. Even secondary use is unlikely in these countries. C. Charreau (PC) writes that the French-speaking soil scientists of Mali, Mauritania, Niger, Senegal, and Upper Volta use the French system in which they have been trained. From time to time, they do attempt correlations with Soil Taxonomy for surveys sponsored by international agencies. Responses from

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individuals contacted in the Netherlands, Scotland, South Africa, and Zimbabwe indicate interest in the system by the leaders in soil science, though it is not used significantly. There has been no inoication that Soil Taxonomy is used in any way in Hungary or the USSR, but the Russian literature on the subject is ample evidence of awareness. It should be noted that soil scientists of Iran may not use Soil Taxonomy currently. Iran is listed under countries using Soil Taxonomy as a secondary system in Table I on the basis of evidence in the older literature.

IV. PROBLEMS FOR USERS OF SOIL TAXONOMY

A. Complexity, Presentation, and Background

With few exceptions, the 53 foreign respondents to the author's inquiry identified the complexity of the system, its presentation, or both as obstacles to its use. Beinroth (1975), Butler *et al.* (1961), Cook (1975), Ragg and Clayden (1973), Stephens (1965), and Webster (1968a) have published the same criticisms. The numbers of taxa and the quantitative precision of definitive criteria require complicated definitions and keys, which demand intense concentration and substantial competence if they are to be applied precisely. The difficulty is magnified by the manner in which these are presented in publishing documents. In many instances, precise interpretation of definitions and keys depends on the presence or absence of a comma or the use of the conjunction "and" or "or." A number of individuals with whom the author has discussed the subject assert that the manner of presentation makes application of the system unnecessarily complicated.

These attributes of the system created problems for field scientists in the United States when Soil Taxonomy was first adopted. Only part of their difficulties could be attributed to the system and its presentation; a significant part was due to their background of qualitative or semiquantitative field methods and thought. This is probably true in other countries where Soil Taxonomy has been used. In the United States, difficulties of applying criteria largely disppaeared for individuals working with a limited range of soils as they gained experience with that part of the system which was relevant to their work. Experience was fortified by special training not only in use of the system but also through the example of supervisory personnel in the methods of quantitative science. Temporary difficulties in application of the system commonly reappear, though to a lesser degree, when even experienced field scientists encounter soils far removed from those parts of Soil Taxonomy with which they are familiar.

These kinds of problems are major obstacles for individuals of countries where Soil Taxonomy is relatively new or is not used regularly. They are especially troublesome where English is not the common language. Respondents to the

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author's questionnaire from 21 countries, including 6 where English is the common language, report that soil scientists classify soils incorrectly in a significant proportion of their placements because of misinterpretation of the keys or definitions. Respondents of only two countries reported that this is not a problem; the author questions their appraisal. Respondents of only three countries where English is not the common language report that translation is a source of error. Others familiar with the work, however, report that translation is a major problem. Buol (PC), responding from his perspective of the work in Latin America, observes that workers who are not fluent in English tend to use narrative descriptions rather than the keys. Consequently, they overlook the order of precedence of criteria, which is critical for classification in the system. He also notes that such problems are "surprisingly few" considering the handicaps under which Latin American soil scientists work.

The author is convinced that the paucity of published information about the evolution of the ideas that shaped Soil Taxonomy and the reasons for seemingly arbitrary decisions about definitions of criteria and distinctions between taxa create problems for those who apply the system. Field personnel he supervised were commonly uncertain about the correct interpretation of keys and skeptical of distinctions until they understood the intent and reasons for it. General principles that control the system have been published in the Seventh Approximation (Soil Survey Staff, 1960), by Smith (1963, 1965), and in the "complete" publication (Soil Survey Staff, 1975). To understand the underlying rationale of the system and the bases of decisions it reflects, however, it is necessary to know relevant detail for an enormous amount of data assembled for thousands of individual soils, the results of testing each of six approximations against these data, the conflicts between theory and fact this testing revealed, and the conclusions from debate about ways to accommodate newly discovered facts. Nowhere is that information generally available, and no individual could assemble it in detail. Nor are the underlying precepts of soil genesis which shaped the system obvious in the literature. The system is presented as a device suitable for application empirically, which the inquiring mind finds both unsatisfying and, in parts, unreasonable. To rectify to a limited degree this enormous gap in background information, the author has recently compiled that part available to him (Cline, 1979), but much more is needed from those more intimately involved in development of the system.

B. Application of Criteria

1. *Field Criteria*

The application of diagnostic features of the argillic horizon was identified as a problem most frequently by respondents to the author's questionnaire. It has also

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been reported as a problem by Kesseba *et al.* (1972), Murthy *et al.* (1977), Nettleton *et al.* (1969), Odell *et al.* (1974), and Van Wambeke (1967). In 1977 Isbell presented a comprehensive summary of difficulties in identification of argillic horizons (scheduled for publication in the transactions of the meeting of Commissions IV and V of the International Society of Soil Science at Kuala Lumpur, Malaysia). The problems focus on identification of clay skins, estimation of their relative volumes, and conflicting evidence for genetic origin of both clay increases with depth and of clay skins. A second paper by Isbell at the same conference, currently unpublished, discusses the problem in relation to soils of Queensland, Hawaii, Brazil, Natal, and Mauritius.

The criteria for plinthite require predicting whether or not the material will harden on exposure. Harpstead (1973) has described assumptions made in such predictions for Nigeria. Daniels *et al.* (1978) have described the problem and have suggested solutions.

The criteria for identifying fragipans are more descriptive than definitive. Deckers (1966) has described some of the problems encountered in the field. From personal experience, the author knows that identification of fragipans is not consistent among workers in the United States.

2. *Laboratory Data*

Inadequate laboratory data is identified as a major problem by respondents from 22 nations. The cost of obtaining the data is considered limiting by respondents from most developing nations. Articles by Beinroth (1975), Butler *et al.* (1961), and Cook (1975) express similar concern. Antoine (1977) noted that for northern and western Africa lack of laboratory data is a serious limitation that can be corrected only by a massive laboratory program, for which resources are limited. Deficiencies of laboratory data were problems in the United States while Soil Taxonomy was being developed, and some individuals were critical of criteria that require them. With the resources of the United States, the deficiency was largely corrected, and soil science advanced enormously as a result. Responses to the author's questionnaire show that supporting laboratory work has increased substantially in several developing nations as a consequence of adoption of Soil Taxonomy. Presumably soil science has advanced in those countries accordingly. Nevertheless, lack of adequate laboratory data is a problem in countries where resources are limited and will continue to be an obstacle to precise use of Soil Taxonomy for the foreseeable future.

There does appear to be some misconception of the amount and sophistication of laboratory data that are essential. Obviously, not every pedon examined can be sampled and analyzed, nor is highly intensive sampling for laboratory work essential for realistic use of Soil Taxonomy. Enough data are needed to establish norms and to identify field clues that will permit reasonable estimates. This is the

pattern followed in the United States. Murthy *et al.* (1977) have noted that reasonable approximations of many criteria can be made without resorting to sophisticated procedures. Cook (1975) reported that realistic estimates of criteria for classification were made in the Sudan even when laboratory data were inadequate for high precision.

3. *Inferred Criteria*

Lack of data to establish soil temperature and moisture regimes is identified as a major problem by a large proportion of the respondents to the author's queries. Ideally, direct measurement of these properties over time is preferred, but the time required, especially for soil moisture regimes, discourages workers in many countries. Consequently, these attributes are commonly inferred from other information.

Uncertainty about estimates of soil moisture regime has been reported much more frequently than about estimates of soil temperature. Cook (1975) reported that estimating soil moisture regimes is a major problem for the Sudan; Antoine (1977), for northern and western Africa; Deckers (1966), for the Belgian Ardenne; Kesseba *et al.* (1972), for Tanzania; Isbell and Field (1977), for Australia and Brazil; and Murthy *et al.* (1977), for India. Antoine (1977) has emphasized that better correlations are needed between soil moisture regimes and both atmospheric climate and plant-water relations for reliable estimates.

Respondents to the author's questionnaire from the U.S. Forest Service and from Canada report that estimates of both soil moisture and soil temperature regimes are unreliable in vertically zoned mountainous areas. Establishing the necessary data base in these areas would be costly and time consuming. Guidelines for estimating soil temperature regime (Smith *et al.*, 1964) provide bases for reasonable approximations of soil temperature regimes in many areas if air temperature data are available. The guidelines need modification for regions where climates and vegetative cover differ markedly from those where the relationships were established.

C. Training and Bias of Personnel

Precise use of Soil Taxonomy demands expertise in field techniques, diligence in their application, and subordination of preconceived ideas about classification of soils. In the United States, Soil Taxonomy forced a major transformation of most of the field staff from qualitative observers in an atmosphere of historically derived concepts to quantitative investigators in an environment of detached reasoning. The transformation was not made easily or quickly, nor is it complete. It has involved intensive training, both formally and informally, which continues

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as new personnel enter service. The system is no less demanding in other countries.

Respondents from 10 foreign countries, including 3 of the developed nations, report that field workers commonly overlook definitive properties or fail to determine them precisely. Cook (1975) reported that inexperienced personnel prepared inadequate soil descriptions and mixed critical horizons when sampling for laboratory studies to determine criteria of the system. Personal communication with individuals who have observed field operations in several countries indicates that errors of these kinds are more widespread than the responses suggest. Buol (PC) comments that essentially all of the leading soil scientists of Latin America are trying diligently to use the system correctly but with too little direction in more than empirical application. These are problems that only experience and training can correct.

Errors in application of Soil Taxonomy are not confined to field personnel. One response to the author's questionnaire, for example, reports need for an "andic" subgroup of Ustox on the grounds that the soil is dominated by clay of high activity. This individual apparently does not understand that the Oxisol order, of which such a subgroup would be a member, is defined specifically to include only those soils which are so highly weathered that clays of high activity would *not* be present. He did not question the concept of Oxisols.

Personal bias is, and probably always will be, a problem of soil taxonomists. (The term bias is not used in a derogatory sense.) It is exhibited among users of Soil Taxonomy in many ways, ranging from sincere disagreement with the system's own bias to intellectual dishonesty in its application. Among the former, a number of respondents to the author's inquiries report that Soil Taxonomy classifies some soils "incorrectly" because it separates them from other soils that are considered members of the same taxon in another system. The most common "problem" of this kind is the complaint that many, if not most, Latosols (Laterite, Lateritic soils) are not Oxisols by criteria of Soil Taxonomy. The complaint may or may not have merit, but the real problem is that individuals base their criticisms on preconceived ideas rather than on the merits of the alternatives.

Respondents from three countries say that some individuals deliberately classify soils incorrectly by criteria of Soil Taxonomy to preserve groupings of another system they have used. Six others report that some deliberately classify incorrectly to show similarities of soil potentials for use. Other misrepresentations of soils in the system arise from the mistaken idea that the system is infallible. Some workers distort or overlook factual evidence to make soils fit the system (Cline, 1977). Wilding (PC) mentions failure to report observations of facts that do not fit the system. These kinds of omissions and distortions conceal errors in the system, which was designed deliberately to expose them.

Most countries that use Soil Taxonomy as a primary system have some provi-

sion for training, if only informally by supervisory personnel. Buol (PC) indicates that this too commonly consists only of instruction in empirical application. India provides one of the more intensive training programs (Murthy, PC). Antoine (1977) has emphasized that in North Africa, where Soil Taxonomy is used little, acceptance of the system would depend on training prior to attempts to have field workers use it. Guerrero's unpublished survey of Soil Taxonomy in the Tropics rates teaching of the system in Latin American universities as generally weak. Teaching and training are likely to remain problems in countries where resources are limited. The needs for training in many countries include instruction not only in use of the system but also in basic soil science and in scientific attitudes and ethics.

V. TAXONOMIC PROBLEMS

Well over 100 "problems" are reported by respondents to the author's questionnaire. Many are local problems for which solutions proposed would adversely affect classification of soils of other areas. Others are problems reflecting the personal bias and incorrect use of criteria discussed in the preceding section. Some are clearly deficiencies of the system and affect classification of soils in the world scene. The major ones of these are discussed here.

A. Need for Additional Taxa

This is the taxonomic problem mentioned most frequently by respondents. G. D. Smith (PC) notes that lack of an appropriate taxon to accommodate unique kinds of soils is a problem he has encountered frequently in his extensive travels. It results in classification of unlike soils in the same taxon. The system was constructed to permit additions (Flach, 1963), so incomplete classification can be corrected. Uninhibited additions of taxa could, however, result in a chaotic mélange replete with contradictions. Some device is needed to weigh the merits of proposed new taxa in terms of the need for them, impact on other parts of the system, and appropriate criteria to define them. The main proposals for additional taxa which have come to this author's attention are reported here, mainly with little comment for lack of bases to appraise them.

Guthrie (PC) reports need for five great groups of Arents based on soil moisture regimes for the southeastern United States. He also suggests alfic, ultic, spodic, ochreptic, and oxic subgroups of one or more of them. Arents are currently unclassified below the suborder level. Isbell (PC) notes the inadequacy of current great groups of Ultisols for Australia. Coover *et al.* (1975) have

proposed Halaqualf and Halaquept great groups with typic, salic, and histic subgroups for 1.5 million hectares of coastal marshlands of the United States. Their analysis of the problem has been reinforced by Coultas and Gross (1975). Westin *et al.* (1968) have reported need for a "Tropoll" suborder for Mollisols of ustic isohyperthermic regimes to distinguish them from Ustolls of temperate regions. The "Trop-" designation may be inconsistent with this use.

Most of the proposals are for additional subgroups. Need for andic subgroups of a wide range of great groups is reported by respondents from regions having volcanic deposits: Alvarado (Costa Rica), Muchena (Kenya), Rijkse (New Zealand), Cline (U.S. Forest Service). These problems are related to those of Andepts discussed later. Need for additional halic, salic, and natric subgroups are also noted by several respondents and authors: Salic Udifluvent (India), Salic Natrargid (Sudan), Natric Torrifluvent (Pakistan), Halic Hydraquent (Coover *et al.*, 1975), salic and salic-natric subgroups of Calciorthids, Camborthids, and Haplustalfs for the Indo-Gangetic Plain (Sehgal *et al.*, 1975).

Langohr (PC) describes a polysequum having a thick cambiclike horizon over an argillic horizon in Belgium. He considers these soils members of an unnamed subgroup of Hapludalfs. Ragg and Clayden (1973) reported unrecognized varieties of Placaquods. Leamy (PC) reports need for an ustic subgroup of Fragiochrepts. Two representatives of the U.S. Forest Service (PC) describe soils that fall in the Paleboralf great group because of their depths to the argillic horizon, yet have a fragipan. These are not accommodated well at present and may justify a new subgroup.

Lewis (1977) has described an Argiudoll with vertic properties and near-ustic moisture regime, which he would classify as an Ustertic Argiudoll. Luzio and Menis (1975) described evidence of illuvial clay in lower horizons of Vertisols, and Luzio (1978) found argillans in some horizons of Pelloxererts, Durandepts, and Xerofluvents. Although potential alfic subgroups may be inferred, this is part of the argillic horizon problem described later. Kesseba *et al.* (1972) have reported need for an alfic intergrade to Ultisols.

Guerrero (PC) reports need for additional subgroups of Ustalfs, Ustolls, and Oxisols in Colombia without specifying kinds. Sherrell (PC) suggests additional subgroups of Durumbrepts and Haplohumults in areas mapped by the U.S. Forest Service. Tan *et al.* (1970) proposed a new subgroup for some Spodosols of the tropics.

B. Soils of the Tropics

Soil Taxonomy (Soil Survey Staff, 1975) calls attention to the fact that the classification of soils of the tropics remained to be tested as the manuscript went

to press. That of Oxisols in particular was described as a compromise of conflicting judgments which might well satisfy no one. Problems that have been found are by no means confined to the Oxisols.

The definition of the Oxisol order, including the range of soils it should encompass, remains a matter of controversy. An international committee has been charged with recommending solutions. Progress by the committee has been slow.

One of the most troublesome problems involves relationships between the Oxisol order and the orders of Alfisols and Ultisols. Soils of extensive areas of the tropics are classified as Alfisols and Ultisols on the basis of presence of an argillic horizon. Many of these soils are characterized by properties associated with clays of low activity not strikingly different from those of the Oxic horizon. The contrast between those soils and their counterparts of the Alfisol and Ultisol orders in temperate zones is striking. The problem is widespread. Camargo (Brazil), Murthy (India), Buol (Latin America), De Alwis (Sri Lanka), Comerma (Venezuela), MacVicar (South Africa), and Ali (Sudan) identify it in responses to the author's questionnaire. Gowaiker (1972), Murthy *et al.* (1977), and Rengasamy *et al.* (1978) have published reports about this problem for India. Van Wambeke (1967) identified the problem early in the development of the system. Sanchez and Buol (1974) have discussed it for soils of the upper Amazon basin; Lepsch and Buol (1974), for Sao Paulo State of Brazil. Isbell and Field (1977) were unable to classify certain soils of Brazil and Australia with confidence in either the Oxisol or Ultisol order because of uncertainty about presence or absence of an argillic horizon. Isbell has described the problem in detail (for the Proceedings of the 1977 International Workshop on Soil Classification held in Malaysia and Thailand). He suggested broadening the definition of Oxisols to resolve it. An international committee has been working on the problem over a period of several years. It has considered a number of options, including definition of special "kandi" great groups of Alfisol and Ultisol orders to accommodate these soils. Firm decisions have not been reached.

Soil moisture regimes for the tropics also remain a controversial issue. Isbell has commented on it in his unpublished paper cited above. An international committee has been formed to recommend a solution, but its conclusions have not been reported.

Reconsideration of great groups for soils of the tropics is also needed (Smith *et al.*, 1975) not only for Oxisols but also for some Alfisols and Ultisols. Among respondents to the questionnaire, Sombroek (East Africa), Murthy (India), Muchena (Kenya), and De Alwis (Sri Lanka) variously report problems differentiating between Pale-, Rhod-, and Hapl- great groups of Ustalfs. Similarly, Buol (Latin America) and Sombroek (East Africa) identify problems distinguishing between Pale-, Rhod-, and Hapl- great groups of Udults, Ustults, and

Aquults. Great groups of soils of the tropics are listed as problems needing attention by McClelland (Soil Conservation Service), but no international committee is known to be assigned the problem at this time.

C. Andepts

The range of properties of the Andept suborder is very broad and is not adequately subdivided in lower categories. Bases can range 100-fold; soil moisture regimes include udic, ustic, and xeric; soil temperature regimes are even more varied. Problems related to this variation have been communicated by G. D. Smith, R. Cline and Warrington (U.S. Forest Service), Williams (Soil Conservation Service), Salgado (Chile), Alvarado (Costa Rica), and Rijkse and Leamy (New Zealand). Identification is an additional problem. The determination of thixotropy, for example, is highly subjective. Cortez and Franzmeier (1972) have questioned the limits for volcanic glass. These problems extend to Andic subgroups of a number of other suborders.

The classification of Andepts is being studied by an international committee. One proposal would elevate the Andepts to order status, which would allow more options for distinguishing varieties by criteria consistent with those of other orders of the system. Proponents argue that this would recognize the character of the group at a level more nearly consistent with its uniqueness. As of this writing, the committee has not made recommendations.

D. Pergelic Soils

Few respondents to the questionnaire mentioned the Pergelic soils, and the literature on applications of Soil Taxonomy to them is limited. Pettapiece (1975), however, has identified major problems in Canada.

Currently, these soils are identified largely as pergelic subgroups of a variety of great groups, permafrost being treated as an "extragrade" property. Pettapiece and a number of authors whom he cites have documented extreme physical processes of disruption and mixing associated with cryoturbation, especially in wet soils. The resulting hummocky microrelief marks an abrupt break in soil character horizontally. Pettapiece finds genetic interrelationships between soils of the depressions and of the hummocks. The cyclic character of the resulting soils has led Pettapiece to the conclusion that the classification of these soils should be analogous to that of Vertisols, perhaps involving a sampling unit that includes depression and hummock as a unit. Pettapiece reported that a committee of Canadian Soil Survey has proposed a "Cryosolic" order in their system, paralleling the Vertisol order of Soil Taxonomy.

In addition to Pettapiece, Tarnocai of the Canadian Land Resource Institute

(PC) deplores the low level in Soil Taxonomy at which soils with pergelic temperature regimes are identified and the lack of good devices to separate cryoturbated soils. McClelland (Soil Conservation Service) lists the classification of these soils as problems demanding attention.

E. Vertisols

Ali (1972) has reported that many of the cracking clays of the Sudan, commonly considered good examples, fail to meet criteria defined for Vertisols. Slickensides may not intersect; gilgai relief may be minimal; and aggregates may be platy instead of parallelepiped in a given soil unit. He also found that the distinction between Chromusterts and Pellusterts on the basis of chroma and the differentiation of subgroups on the basis of color value do not make the most meaningful distinctions. He reports that hue is useful in some instances.

G. D. Smith (PC) lists Pellusterts and Chromusterts as groups presenting serious problems due to low correlation of chroma with drainage or erosion. He also cites failure to use acidity as a criterion for soil families as a deficiency. Murthy (PC) reports similar conclusions about use of chroma for India, as does Comerma for Venezuela. Comerma (PC) suggests also that a suborder of Aquerts is needed.

Luzio (PC) reports a need for salic and natric subgroups of Xererts. Luzio (1978) and Luzio and Menis (1975) have described weak argillans in deep horizons of soils classified as Vertisols; Comerma (1971) reported uncertainty about distinguishing between Vertisols and vertic varieties of Alfisols, which may be related to Luzio's findings.

F. Diagnostic Criteria

The weighting, definition, and role of the argillic horizon are subjects of much controversy. The horizon is used in Soil Taxonomy as a mark of the illuviation of clay, which is weighted heavily in the system on the belief that it is an extremely important genetic process. Its definition is based on properties believed to be evidence of that process and allows for limits of observation and measurement. Problems of identification and those involving the horizon in Alfisols and Ultisols having low-activity clays have been discussed in preceding sections.

Isbell (paper for publication in the 1977 transactions of Commissions IV and V, International Society of Soil Science, Kuala Lumpur, Malaysia) has summarized much of the criticism. He questions the genetic implications attributed to the horizon, as does Langhor (PC). MacVicar (PC), Isbell, and others believe that Soil Taxonomy weights illuviation of clay too heavily by using the argillic horizon as a criterion at the highest level in the system. Much of the problem with

Alfisols and Ultisols having low-activity clays can be attributed to its use at that level. Isbell as well as Nettleton *et al.* (1969), Gile and Grossman (1968), and Beinroth *et al.* (1974) have cited evidence that the presence or absence of argillans is not infallible proof that illuviation has, or has not, been significant. Oertel (1968) contended that the ratio of fine to total clay is not a trustworthy criterion. Bullock (PC) questions the universal validity of both criteria. Few soil scientists appear to question the significance of argillic horizons at some level in the system, but many are critical of its definitive criteria and the weight given to it. It has been this author's observation that field personnel commonly "stretch" the defined limits in their enthusiasm to find the horizon.

Problems with criteria of the spodic horizon have persisted throughout the development of Soil Taxonomy and to the present. Avery *et al.* (1978) found that chemical criteria exclude from Spodosols many soils which are "spodic" by morphology. Witty (Northeastern States), Stout (Midwestern States), Gardiner (Ireland), Schelling (Netherlands), Lag (Norway), Ragg (Scotland), and R. Cline (Forest Service) support that observation in personal communications. McClelland (PC) lists criteria for the spodic horizon as a problem the Soil Conservation Service is studying.

Criteria of wetness continue to cause problems in some soils. Pilgrim and Harter (1977) have reported that masking of low chroma mottles by iron and humus of the spodic horizon results in inclusion of a high proportion of wet Spodosols in Typic Haplorthods. Lavkulich (PC) also identifies this as a serious problem. Buol (PC) has difficulty with soils that classify as Typic Paleustults because chroma is not less than three, though the water table may be within the solum for long periods. Avery (PC) also describes water table studies which show that wet soils do not necessarily have mottles of two chroma or less. He attributed significance to ferruginous mottles in some soils. Sehgal and Sys (1970) have reported difficulties with criteria of wetness in the Punjab.

G. Miscellaneous Problems

In addition to the major problems discussed above, a number of relatively less widespread difficulties were reported by respondents to the author's inquiries or were found in the literature. Examples of these are described here, excluding those which were clearly related to misinterpretation of criteria or to personal bias.

De Bakker (1971) reported that stratification in soils of Dutch fluviatile and marine sediments appears to occur capriciously locally. As stratification is the critical criterion determining presence or absence of gleyed cambic horizons in these soils, Aquents and Aquepts are intimately intermingled with little apparent relation to landscape units or differences in genesis.

Both Fenton and Stout (PC) are concerned with application of criteria for the

mollic epipedon to eroded former Mollisols in the midwestern States. Technically, the eroded soils are no longer Mollisols, but they are intimately intermingled with Mollisols in the landscape.

Both Avery and Clayden (PC) report that base status as a definitive criterion separates Eutrochrepts and Dystrochrepts in an intricate rectangular pattern where a long history of liming has changed the base saturation of soils in some fields but not in others. Avery also reports that man-made mollic epipedons create analogous complex patterns of soils distinguished at the order level.

The foregoing are mentioned because they all represent mapping problems as artifacts of the system. Devices exist for handling such geographic mixtures in legends, but they are commonly awkward. As some respondents have indicated, changes to accommodate such situations may well create others elsewhere.

Some difficulties have been reported for the clay mineralogy criteria at the family level. Witty (PC) reports that the definition of oxidic mineralogy classifies many soil series of New England in oxidic families. These are soils on very young glacial deposits. De Alwis (PC) reports problems distinguishing between oxidic and kaolinitic mineralogy in Sri Lanka. Fenton (PC) finds that failure to differentiate montmorillonitic and illitic mineralogy in fine loamy and fine silty families detracts seriously from the interpretive value of soil families in Iowa.

Comerma (PC) has difficulty rationalizing the classification of those Haplustalfs that lack zones of carbonate accumulation in the udic subgroup when they clearly have an ustic moisture regime. Both Murthy and Nanda (PC) report the same problem with Udic Haplustalfs and Udic Paleustalfs in India. Scoppa (PC) is faced with a "pale-" great group of Mollisols having a udic moisture regime but with petrocalcic horizons. The key classifies these as Paleustolls.

Sehgal *et al.* (1975) have reported that soils having salinity or sodicity limitations on the Indo-Gangetic Plain do not key out of typic or aquic subgroups of Calciorthids, Camborthids, and Haplustalfs. They have proposed salic and salic-natric subgroups.

Both Leamy and Williams (PC) write that bulk density requirements keep some soils having other properties of andic subgroups out of those taxa, with serious consequences for interpretation. R. Cline (PC) reports from the Forest Service that some soils are classified as Andic Dystrochrepts by methods defined for base saturation, though research indicates that the soils are nearly base saturated at the pH of soils in the field.

VI. IMPACT OF SOIL TAXONOMY INTERNATIONALLY

A. Soil Classification

The impact of Soil Taxonomy on soil classification internationally varies from adoption of a few concepts or terms in some countries to use as a primary system

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in others. The evidence for impact in countries that have not adopted the system consists mainly of similarities between the innovative aspects of Soil Taxonomy and those of other schemes. Such evidence must be appraised cautiously. Some similarities might have developed independently. Others are known to be the result of ideas that originated with foreign soil scientists and were incorporated in Soil Taxonomy. The author has tried to confine his reporting to those aspects that would probably have taken somewhat different form in foreign countries had Soil Taxonomy not been available *and* to those that evolved through mutual exchange of ideas internationally at the initiative of Dr. Smith and his associates.

The Canadian soil classification (Clayton *et al.*, 1977) is most nearly like Soil Taxonomy among systems in general use. Although it differs from Soil Taxonomy somewhat in organization and uses different names, the greatest difference in principle is probably its use of diagnostic features that may easily be altered by man. The two systems were developed with frequent interchange of ideas, though they were not the results of a joint effort.

The soil classification for the Soil Survey of England and Wales (Avery, 1973) departs substantially from Soil Taxonomy but uses quantitatively defined criteria, a three-dimensional "profile" comparable to the pedon, and some criteria and terms of Soil Taxonomy. Ragg and Clayden (1973) noted that Soil Taxonomy had prompted scrutiny of traditional British soil classification. The new French taxonomy (Fauck *et al.*, 1979), like Soil Taxonomy, uses genetic theory with a strong bias for practical application, though the weighting of elements of genesis is greatly different. It uses the pedon and polypedon concepts. The nomenclature is similar in construction, though the terms are mainly different.

The FAO legend for the soil map of the world (FAO-UNESCO, 1974) is used as a primary or secondary classification in many countries. Although far from similar in outline and detail, it uses many of the devices of Soil Taxonomy. The nomenclature of some parts is similar in construction. Diagnostic horizons defined quantitatively are used as criteria; many are identified by terms used in Soil Taxonomy and are defined similarly. The correlations of the map units with taxa of Soil Taxonomy, however, are far from perfect (Beinroth, 1975).

Rauta (PC) reports that Soil Taxonomy has influenced soil classification in Romania through increased precision of definitions and use of some of its diagnostic criteria. Some soil orders are the same. Thailand (Dent and Changprai, 1973) classifies soils by Soil Taxonomy, though it uses a national system for local use. Gardiner (PC) reports introduction of quantitative criteria from Soil Taxonomy into the system used in Ireland.

Laker (PC) writes that the Seventh Approximation had a revolutionary impact on perspective of soils in South Africa, though a greatly different classification is used. Oyama (PC) states that "without the Seventh Approximation and Soil Taxonomy, soil science in Japan would be far from science. In that sense, the

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influence of Soil Taxonomy in Japan cannot be written." This kind of impact is probably more important to soil classification world-wide than the adoption of specific concepts and devices in individual countries.

B. Soil Surveys

1. *Soil Survey Operations*

In the United States, Soil Taxonomy brought about an enormous increase in the precision and detail of field descriptions and a large increase in both kinds and numbers of supporting laboratory determinations. More importantly, it transformed the field force by necessity from qualitatively oriented observers to quantitatively inclined investigators. It had relatively little impact on the field methods of surveys, but it substituted quantitative criteria for much of the personal judgment that had dominated soil correlation and the development of legends.

In the other 11 countries that use Soil Taxonomy as a primary system, the impact has been much less. Individuals from 9 of the 11 countries responded to the authors inquiries about the impact on soil surveys. All except the respondent from Pakistan report an increase in both the detail and the precision of field descriptions. Respondents from Argentina, Chile, Colombia, India, New Zealand, and Venezuela report an increase in laboratory support, mainly by the addition of determinations required for diagnostic criteria. The total input of laboratory technician time, however, ranges from a high of 14 man-years to a low of 0.25 man-year annually.

Correlation in the soil surveys of developing nations of this group is notoriously weak. Responses to the author's inquiries show that only New Zealand, Venezuela, and Colombia use the criteria of Soil Taxonomy both to define mapping units in field legends and to correlate mapping units when the field work is complete. In Argentina, India, and the Sudan, the criteria of Soil Taxonomy are apparently used mainly *after* field work is complete to combine some units for publication and to correlate the published units with taxa of Soil Taxonomy. Murthy (PC), for example, reports that correlation of the 700 soil series established for mapping in India is only beginning.

The situation in India is analogous to that in the United States in the 1950s, though the number of established series is much less. Soil Taxonomy required major revisions of existing soil series definitions before its criteria could be applied consistently in the development of legends for detailed surveys. Similar adjustments will be a major undertaking in countries that adopt the system. Some appreciation of the size of that task, including the necessary training, may be obtained from Cook's (1975) report on use of Soil Taxonomy in the Sudan.

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Indirect impact of Soil Taxonomy on soil survey operations is reported by respondents from Canada, Kenya, Sri Lanka, Trinidad, Romania, Ireland, Brazil, England, Japan, Belgium, and Costa Rica among countries that use the system only in a secondary role. They indicate that standards of precision, detail, or both have increased to some degree for field descriptions. Six of the 11 also report addition of new laboratory determinations for criteria used in classification. One respondent from Australia, which uses the system little, mentions some effect on field descriptions and addition of a few laboratory determinations.

2. *Soil Maps and Mapping*

a. Soil Boundaries. Orvedal and Austin (1963) predicted little change in the number and location of soil boundaries in detailed soil surveys of the United States as a consequence of Soil Taxonomy. The boundaries of most delineations are based on the visible landscape. The *identity* of some mapping units did change as soil series were redefined and new series were established, but soil scientists contacted in the United States confirm that the effects on mapping were small. Six individuals report that "some" additional boundaries are drawn to accommodate criteria of Soil Taxonomy. Only two say that "some" boundaries that would have been drawn previously are located differently.

Orvedal and Austin (1963) also compared compiled maps using the 1938 system with maps based on Soil Taxonomy for scales of 1:5,000,000 and 1:20,000,000. They found that some adjustment of boundaries was necessary, mainly to accommodate the new soil temperature and soil moisture criteria that Soil Taxonomy introduced.

Respondents from five foreign countries that use Soil Taxonomy as a primary system report that mappers use its criteria to make distinctions in the field. Only three of the five, however, report that the criteria are incorporated in legends; one may assume that use of the criteria is minimal for the other two. Four report that "some" boundaries that would not otherwise have been recognized are drawn; only two report that the location of other boundaries is affected. All of those reporting a significant impact on mapping are from countries where mapping intensity is less than for detailed soil surveys of the United States and where quality control has historically been poor.

Respondents from eight countries where the system is used only in a secondary role report that soil mappers do use some of its criteria in the field. Respondents from Belgium, Brazil, Romania, and Sri Lanka report that some new boundaries are drawn as a result. None consider that location of other boundaries is affected significantly.

b. Purity of Mapping Units. If, as reported, the location and number of soil boundaries drawn in the field is affected little by using Soil Taxonomy, it follows that the change of soil variation within delineations should be equally small.

Assuming that any relocation or addition of boundaries accurately reflects adjustment to conform with new criteria, any change in purity should be positive *when measured against composition according to taxa of the new system.*

Experience in the United States shows that the *apparent* purity of mapping units of detailed soil surveys may decrease when the criteria of Soil Taxonomy are applied as the basis of measurement. In an extreme instance, McCormack and Wilding (1969) studied the composition of mapping units in an area having intricate patterns of soils in stratified lake sediments. They measured the composition of delineated areas in terms of soil series present, first using concepts of series that predated Soil Taxonomy and then using series defined by the limits of criteria of the new system. They found that the proportion of the total area outside the ranges of series named increased by about one-third. Although the areas were not remapped using criteria of Soil Taxonomy, it has been this author's experience in similar areas that mapping would have changed little.

The apparent increase in inclusions is mainly an artifact of the quantitatively defined limits of taxa. The limits of criteria of all categories accumulate as limits of soil series. Thus, a pedon selected from a polypedon identified as a series of a coarse loamy family is outside the range of its series if it contains 19% clay—1% above the upper family limit. The accumulated limits at the series level cleave conceptual "splinters" of soil of another *potential* series from soil bodies that are identifiable as natural units. Commonly, these differ in only a minor degree of one or two properties from the series identified in mapping. Many are unclassified at the series level. The term "taxadjunct" has been coined to characterize unclassified soils that differ from established series to such a minor degree that soil potential for use is substantially the same. These are treated as if they were members of the parent series for practical purposes.

c. Quantitative Limits. The discussion of the preceding section leads to reconsideration of quantitative limits and their application to bodies of soil in the field. The quantitatively defined criteria of Soil Taxonomy have been identified as one of the system's most laudable attributes by 22 of the respondents to the author's inquiries and by authors such as Antoine (1977), Beinroth (1975), Butler *et al.* (1961), and [illegible]g and Clayden (1973). It is the characteristic of the system that has had the greatest impact on soil science in general, soil classification in particular, and the scientific attitudes of soil survey workers. Webster (1968a, 1968b) has emphasized, however, that the absolute limits of Soil Taxonomy are not consistent with the errors of estimates of criteria in practice. Wilding (PC) expresses similar concern and notes that too few field workers appreciate the errors inherent not only in observation and measurement but also in field sampling.

It is apparently not commonly appreciated that precise definition of limits for differentiating criteria does not *a priori* imply unyielding application of those limits to the conceptual boundaries of taxa. Wilding (PC) contends that although

limits of criteria should be defined in terms of single values, as at present, they should be applied to boundaries of taxa with latitude for variation consistent with the probable error of the estimate. To carry that idea one step further, not only could the degree of allowable departure from defined "limits" be prescribed but also how many criteria in combination might be permitted to violate their "limits" to that degree for determining the boundaries of taxa. This is effectively what is done in the definition of taxadjuncts, most of which would become members of their parent series in concept as well as in practice if such a device were adopted as general procedure. Such a convention would require substantial study and testing, and it would probably result in some loss of consistency of classification among individuals. It might, however, provide solutions to a number of the "problems" reported by respondents to the author's questionnaire.

C. Interpretations for Applied Objectives

A sharp distinction is made in this section between the evaluation of soil taxa for applied objectives and predictions about potentials, limitations, and management needs of the real bodies of soil that are identified by the names of taxa on soil maps.

1. Evaluation of Taxa

Bartelli (1978) has listed 11 objectives for which soil surveys are routinely interpreted in the United States. Although these interpretations are presented as predictions for mapping units that represent real soil bodies, they are, in fact, based mainly on the defined attributes of the phases of soil series used to name the mapping units. They do not usually evaluate the effects of the inclusions that are normally present.

Phases of soil series are not new to Soil Taxonomy; comparable units would have been identified and interpreted if Soil Taxonomy had not been developed. Respondents of the Soil Conservation Service, the Forest Service, and several states report, however, that Soil Taxonomy has resulted in significantly more precise interpretation because of the quantitative limits it has imposed on the range of properties of soil series. It should be understood, however, that this increase of precision applies mainly to conceptual units of classification, not necessarily to the real bodies of soil that are identified by their names.

Respondents from Argentina, Chile, India, New Zealand, the Sudan, and Venezuela report that adoption of Soil Taxonomy has increased both the precision and number of soil interpretations. Respondents from 4 of the 10 countries where Soil Taxonomy is used only as a secondary system report some increase in

precision. The author would judge that the impact has been relatively small in all of these countries, which have either adopted Soil Taxonomy very recently or have limited programs for soil interpretation. As in the United States, increased precision applies primarily to taxonomic units, not mapping units.

The foregoing refers mainly to interpretations for phases of soil series or their equivalents. Orvedal (1977) has stressed the sacrifice of information on which interpretations can be based as the taxa increase in heterogeneity from soil series to higher categories. Westin (1974) showed that the coefficient of variability of the selling price of land approximately doubled from strata representing soil series to strata representing orders. Chan (1978) found that soil series are correlated with productivity of *Hevea* in peninsular Malaysia; he could assign subgroups to five classes of productivity but the range of variability within subgroups was large. He found that the range of productivity was very large within great groups, though the best clones of *Hevea* realized their full potential only on soils of a few specific great groups.

While the range of soil properties within taxa increases from series to families, phases of soil families are believed by a number of workers to be homogeneous enough to serve as basic units for transfer of technology on a broad geographic scale. Uehara (1978) has described the rationale for this function of the family. Preliminary results of research to test the hypothesis have been published (Anonymous, 1978). North Carolina State University uses soil families to provide unequivocal identity of soils at experimental sites in the tropics (Soil Science Department, 1978). Respondents to the author's questionnaire suggest that soil families are suitable taxa for characterizing the soil factor in some Forest Service land inventories for predicting forest productivity, revegetation potential, soil stability, and similar elements of forestry operations. Respondents from India, New Zealand, the Sudan, and Venezuela report that soil families have been tried and have proved useful for some applied interpretations, but their experience is limited.

At successively higher categorical levels, the range of properties within taxa obviously restricts soil interpretation to increasingly broad objectives. Nevertheless, respondents from five countries report interpretive value of taxa at levels as high as the suborder. Ten cited the introduction of soil climatic parameters at a high level as an important element for enhancement of the interpretation potential of taxa of the higher categories. Ikawa (1978) has discussed this in some detail. It is possible, for example, to identify soils in which wetness is limiting at the suborder level. Specific examples of interpretations for taxa above the family level are rare, however.

Others report deficiencies of Soil Taxonomy as a base from which applied interpretations can be made. Stephens (1963) criticized the system because it separates similar soils in Australia and reduces the correlation of taxa with land use potential. This is not a unique attribute, nor is it limiting. Soils of similar

potential are classified in different taxa in most, if not all, taxonomies and are routinely grouped in technical classifications for applied uses (Bartelli, 1978).

Problems are more serious if Soil Taxonomy fails to distinguish between soils of unlike potential. Instances of this kind reported by respondents include the following:

1. The range of soil temperature regimes is too wide.
2. Soils having fragipans are not distinguished from "pale-" great groups.
3. Color criteria of Vertisols do not make meaningful separations.
4. Some soils with pronounced ustic moisture regimes are classified as udic subgroups.

Buol (PC) reports that failure of the system to make distinctions on the basis of properties of surface horizons leaves soils having significantly different potentials for primitive farming in the same taxon at the family level. Buol's concern is with the loss of confidence of soil scientists who expect too much of the system—not with the omission of properties of surface horizons. The examples given above are, of course, appropriate criteria for soil series or for phases of families.

None of the deficiences reported is unique in principle to Soil Taxonomy nor is insurmountable if the principles and techniques of soil interpretation are understood. Low levels of technological understanding are more critical than deficiencies of the system. Guerrero's survey of Soil Taxonomy in the Tropics, for example, reports vigorous criticism because (1) the taxa are not interpretive groups and (2) the interpretive potential decreases from low to high categories. Both of these attributes are characteristic of any hierarchal taxonomic system. It is quite possible that the subtitle, "A Basic System of Soil Classification for Making *and Interpreting* Soil Surveys," has unwittingly inspired expectations of direct interpretive meaning of the taxa for workers having weak technical backgrounds.

2. *Predictions for Map Units*

These entail predictions that encompass soil potentials of not only the taxa identified in map unit names but also the inclusions and, in addition, the effects of interactions between the two on use of land areas. Almost all interpretations of detailed soil surveys consider only the taxa identified in names. Soil Taxonomy has had essentially no effect on this practice. The system has increased the precision of predictions for the named taxa, but if as indicated in Section VI,B,2 it has had little effect on mapping, the net error of the predictions for delineated areas should have increased.

From personal observation, the author believes that the "purity" of mapping units in terms of soil potentials for use has increased substantially in detailed soil

surveys of the United States over the past 15 years, but not as an effect of Soil Taxonomy. During that period the pressures for both greater variety and greater accuracy of predictions about the potentials and limitations of soil mapping units have increased dramatically. These pressures have been translated into legends tailored for predictive value and into greater diligence on the part of mappers. Mappers strive to exclude from their delineations small areas of soil having markedly lower potential than the taxa identified in the names. They are less concerned with small inclusions of soil having higher potential. The fact that mappers may still be located where they can be held accountable when some users apply the predictions is a potent compulsion for diligence. These elements are largely lacking in other countries that use Soil Taxonomy.

Interpretation of small-scale maps is a neglected subject in soil science. Most of those that have been made are primitive. Orvedal (1977) has emphasized the loss of geographic information and its precision as map scale decreases. Interpretations that can be made must be correspondingly general in purpose and in geographic detail. Small-scale maps based on Soil Taxonomy or any other taxonomic system can be interpreted only within these limitations.

It is common misconception that units of small-scale maps can be identified with precision in terms of taxa of higher categories. At small scales and correspondingly large minimum size of mappable areas, soil heterogeneity within delineations necessarily is large. No taxonomic device can alter that fact. When map units that represent large land areas are identified by taxa of high categories, part of that heterogeneity is represented by the broad ranges of the taxa; the remainder can be identified in terms of the contrasting taxa present. If the taxa have strong geographic bias, the latter can be minimized by appropriate location of boundaries.

There is strong geographic bias in the Alfisol, Aridisol, Mollisol, Oxisol, Spodosol, and Ultisol orders of Soil Taxonomy. Sehgal and Sys (1970) have correctly noted, however, that the Entisol, Inceptisol, Histosol, and Vertisol orders have much more limited geographic connotations. Areas of Entisols and Inceptisols ranging from a fraction of a hectare to a few thousand hectares, for example, are commonly intimately intermingled with areas of one or more of the six orders that have stronger general geographic connotations. Consequently, soil map units at scales so small that minimum delineations represent hundreds of square kilometers are typically geographic mixtures of contrasting soil orders. At the suborder level, soils having aquic moisture regimes are separated from their nonaquic counterparts of the same order. These contrasting taxa at the suborder level are typically even more intricately intermingled in the landscape and cannot be delineated separately on small-scale maps. Thus, prediction of the soil potentials of the large areas mappable at small scales usually involves appraisal of geographic mixtures of contrasting soils, even though they may be identified at the highest levels of Soil Taxonomy.

Small-scale maps, like those of Aubert and Tavernier (1972) and Moorman and van Breemen (1978), identify map units in terms of one or a few dominant taxa at the highest levels of Soil Taxonomy, but it is understood that the areas are likely to contain major proportions of soils that may be highly contrasting. The maps at larger scales produced by the low-intensity surveys common in developing nations also delineate intimate mixtures of soils that not only are members of different taxa of Soil Taxonomy but also have markedly different potentials for use. Many maps of this kind identify map units in terms of a single dominant taxon and thereby lose much of their potential interpretive value. The kinds, amounts, and patterns of associated contrasting soils are commonly not recorded. Buol (PC) reports that many workers in Latin America are disappointed and critical when they discover that such map units cannot be interpreted with confidence for the site-specific requirements of small farms.

Even if the composition of map units is known, relatively few soil scientists have the understanding and experience with geographic interpretations to take advantage of the potential such soil maps present. Most predictions for them stop with generalizations based on the dominant taxa. While the data do not permit site-specific predictions, they do provide the information necessary for quantitative estimates of the relative proportions of map units having different soil potentials. They also provide the information necessary for estimates of probability that soil of a given potential will be found at a given site. Cline and Marshall (1977) have published an interpretation of this kind.

VII. SUMMARY

Response to international distribution of Soil Taxonomy has ranged from acceptance as an official system to absolute rejection. The scheme is used as the primary classification for national soils programs in 12 countries. It is used commonly by soil scientists of 19 other countries for international communication, though the national programs of these countries depend on other systems. It is used infrequently in 20 others for which information is available. In a few of the latter, it is rejected almost completely.

The system addresses the world-wide range of soils in detail. Its scope is praised by advocates; the complexity which this attribute necessarily entails is deplored by critics. Among its innovations, the use of quantitative criteria and concepts of diagnostic horizons are acclaimed by its supporters; the complicated definitions and keys that result are cited as defects by many. The innovative nomenclature is welcomed by some but condemned by others.

Problems in applying the new approaches and criteria developed for Soil Taxonomy were inevitable. Some have been problems inherent in its potential users, such as personal bias and lack of training and experience. Deficiencies in published explanations of reasons for the choice and application of criteria have

created an appearance of empirical or capricious decisions and uncertainties among some of its potential users.

Some attributes of the system itself are obstacles to users. The system is highly demanding, and the manner in which it is presented in published form magnifies the problem. Some field criteria, such as those for argillic horizons, plinthite, and fragipans, are difficult to apply with precision. Lack of laboratory support for determination of some criteria and lack of data from which soil moisture and temperature regimes can be estimated have been cited by many as obstacles.

The system is still in a process of evolution as data about soils of the world accumulate and expose taxonomic problems. Need for additional taxa, which can be accommodated, has been reported by many users. The system is incomplete for soils of the tropics. International committees have been appointed to consider the definition of Oxisols, the problems with soils having low-activity clays and argillic horizons in the tropics, and the questions about soil moisture regimes for these regions.

A committee is studying a more nearly adequate subdivision of the Andept suborder, including the possibility of elevating the group to order status. Workers in regions of cold climates find classification of cryoturbated soils associated with permafrost inadequate. The criteria for subdivision of Vertisols, and for distinguishing the Vertisol order, do not everywhere make the distinctions anticipated. Taxonomic problems with some diagnostic horizons and several criteria have been found. Among these, the validity of the heavy weight given the argillic horizon in the system is questioned by many. Criteria for the spodic horizon continue to be troublesome. The criteria of wetness appear to need adjustment for some soils.

The impact of Soil Taxonomy on soil classification world-wide has been far greater than that of any other development in the discipline during the past 50 years. In addition to its use as a primary system in 12 countries, elements of its principles, concepts, and devices have been incorporated to varying extent in both general and national schemes used in many countries. More importantly, it has prompted a changed perspective of soils and the beginnings of transformation from a qualitative to a quantitative approach to soil classification in many countries. The impact on soil surveys and soil interpretations has been much less.

Major improvements remain to be made. Among these, devices that will adapt quantitative limits of criteria more realistically to soil variation in the field are needed to reconcile the conceptual framework of taxonomy with the reality of soils in nature.

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AGROTECHNOLOGY TRANSFER IN THE TROPICS BASED ON SOIL TAXONOMY

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I. INTRODUCTION

Agricultural production capacity in the less developed countries (LDCs) of the tropics must be expanded by increases both in the yields per hectare and in the area of cultivated land. This growth in resource productivity, however, should be guided by wise land-use decisions and based on sound methods of soil and crop management. Since most LDCs lack the trained manpower, the capital, and the institutional capacity to conduct all the research required to fill their needs in the short time available, it stands to reason that they should capitalize on experience gained elsewhere under conditions of similar ecology and factor endowment.

The groundwork required to transform agriculture in the tropics from a natural resource-based enterprise to an industry founded on science and technology is now gradually being generated through research and development in many agencies and areas. Although there has been a lag in the large-scale dissemination and systematic application of this knowledge, transfers of applicable agrotechnology are of such critical importance to the agricultural and economic development of agrarian LDCs that they must now be facilitated.

In the context of this perspective, this paper outlines the rationale, prospects, and limitations of an approach to the transfer of agroproduction technology that is based on soil classification. Although the scope of the paper is broad, reference is made to a research program of the Universities of Hawaii and Puerto Rico, the Benchmark Soils Project, to exemplify and substantiate some of the general statements with factual data.

II. THE TRANSFER OF AGROTECHNOLOGY

A. General

International transfer of agricultural technology is not new. Diffusion of husbandry practices and information about crop varieties and livestock breeds was a major source of productivity growth even in prehistoric times (Sauer, 1969). It is also well known that, after the discovery of America, the introduction of new cultivars from the Americas to Europe had a profound impact on European agriculture. This "natural diffusion" in preindustrial time was largely a by-product of nonagricultural human endeavors, characterized by long periods of gestation and delivery. The modern institutionalization of agricultural research and extension significantly expedited the process of dissemination, as evidenced by the recent promulgation of high-yielding varieties of rice and wheat in many tropical and subtropical countries. This apparent success, however, cannot obviate the extreme complexity of the transfer of agrotechnology. Only in recent years has this complexity become reasonably well understood (Wortman, 1976).

There are fundamental differences in the conditions that must rule the transfer of technology to the industrial and the agricultural sectors in developing economies. In the industrial sector, new industries can be established with minimal disturbance of the institutional framework of a country; in contrast, technology transfer in the agricultural sector must confront the attitudes and institutions that have so long held these rural societies stagnant (Myrdal, 1974). Also, whereas the transfer of industrial technology from developed to less-developed countries can be quite direct, the transfer of agricultural technology, particularly the biological component, is generally not possible. There is now a growing consensus that much agricultural technology is location specific and a function of the physical, biological, and socioeconomic conditions of the environment where it has been developed. The corollary of this statement is that, in order to be productive, "much of the agricultural research must be conducted and the results analyzed, tested, interpreted and applied within a relatively decentralized system" (Hayami and Ruttan, 1971). Thus, the technology for tropical agriculture must be developed primarily in the tropics.

Inadequate appreciation of the location specificity of agricultural technology was a major reason for the lack of effectiveness of much of the technical assistance effort by national and international agencies in the 1950s and 1960s (Hayami and Ruttan, 1971). The "diffusion model" that, explicitly or implicitly, was the underlying rationale for technical assistance after World War II led to an "extension bias," which, as Moseman (1970) pointed out, "met with only limited success because of the paucity of applicable indigenous technology and the general unsuitability of U.S. temperate zone materials and practices to tropical agriculture conditions." In a similar vein, Kamarck (1972) observed that the tropics are littered with ruins of agricultural projects that refused to recognize the special conditions prevailing there. The Groundnut Scheme in East Africa (Wood, 1950) is probably the best-known case history among these failures.

With only few exceptions, recent writings about economic development problems have largely ignored the possible influence of the environment on economic development, and, reflecting the economists' temptation to find universal laws, the purely mathematical growth models make no provision for environmental variables (Kamarck, 1972). Boulding (1970) touched on this point, noting that the principal failure of economics has been in the field of economic development and wondering "whether culture-boundness may not have something to do with this relative failure."

In this decade, a new perspective has emerged, tying the relative contribution of agricultural and industrial development to national economic growth. There has been a marked shift away from an earlier "industrial fundamentalism" to an emphasis on the significance of growth in the agricultural sector for the total development process (Hayami and Ruttan, 1971). It is now held that agricultural development in the LDCs should serve the dual purpose of securing increases in

both yields and employment. This should be achieved through agricultural technology that engages the latest results of scientific research adjusted to the highest possible utilization of the labor force (Myrdal, 1974). Agriculture is thus viewed not only as a necessary condition for meeting food requirements but also as a productive source of economic growth, and it is considered the best route to economic advancement for the agrarian LDC's (Hayami and Ruttan, 1971; Wortman, 1976).

Rapid improvement of agricultural productivity in LDC's, consistent with required growth rates in the range of 3 to 6%, implies a transition from a natural resource-based agriculture to a science-based agriculture. To bring about this transition within a short period of time requires massive inputs of capital and research personnel. Many of the LDC's are small in size and population, however, and in view of their limited experiment-station capacity, an inelastic supply of scientific and technical manpower, and a general lack of capital, such nations cannot expect to generate by themselves the full range of scientific knowledge and expertise needed to develop and sustain a viable agriculture. They rely on assistance from external sources. The transfer of agroproduction technology, therefore, is critically important to the agricultural, and hence the overall, economic development in agrarian LDC's.

B. Role of Soil Survey and Classification

The site specificity of agricultural research and technology, mentioned in the preceding paragraph, results in large measure from differences in two environmental variables, soil and climate. In the tropics, as in the temperate zone, there is wide variability in both these factors, however, systematic groupings can be made to stratify the population of soils and climates. The seemingly infinite diversity can thus be reduced to a finite number of discrete entities with a limited range in characteristics that conform more nearly to agricultural management units and define the applicability of agronomic research. Because soils and climate are interrelated, both can be combined in one system of classification, as has been done in Soil Taxonomy, the U.S. system of soil classification described in Section III. Thus, Soil Taxonomy, as the basis for soil interpretation, has the best potential for identifying agricultural land and consequently for the transfer of agrotechnology.

Soil classification provides pragmatic groupings of soils for precise predictions about soil behavior, and its most important application is in soil survey. Historically, soil surveys have been geared to the improvement of agriculture, and most LDC governments presently support soil survey activities because they believe soil surveys supply reliable and accurate information for agricultural development and soil-resource management. Soil surveys, however, are only useful if

they follow reasonable scientific standards and if they are interpreted for practical purposes. Such interpretations are predictions of soil behavior under stated conditions, which require the careful synthesis of many data in relation to soil qualities that are the result of the interaction between soil characteristics, crop requirements, and management practices (Kellogg, 1961). In fact, soil survey interpretation makes possible the most intensive use of soil science by integrating knowledge from many other disciplines (Smith, 1965).

It is an implicit rationale of soil survey interpretation that soils classified in the same taxa have a common response to management practices.

> We make the basic assumption that experience with a particular kind of soil in one place can be applied to that particular kind of soil wherever it exists if consideration is taken of any climatic differences. The soil survey acts as a bridge that lets us transfer the knowledge gained by research or by the experience of cultivators from one place to all other places where it is applicable (Smith, 1965).

There are inherent constraints to this approach to knowledge transfers, however, relating to the nature of taxonomic soil classification, certain inadequacies in the classification of tropical and subtropical soils, and the restricted availability of soil-specific agronomic information. Moreover, transfers of agrotechnology based on soil classification cannot completely circumvent the need for on-site experimentation. Such transfers, however, can help avoid duplication of effort, maximize the utilization of knowledge generated elsewhere, and give direction to the kind of adaptive research required to adjust soil and agronomic experience to particular local conditions. Within these qualifications, soil survey and classification provide an effective basis for the scientific transfer of agrotechnology.

C. Kind and Availability of Transferable Information

Transfers of both the mechanical and biological components of agricultural technology can occur through (1) material transfers, (2) design and knowledge transfers, and (3) capacity transfers (Hayami and Ruttan, 1971). This paper is primarily concerned with knowledge transfers, which should be conducive to the production of locally adaptable technology after a prototype technology has been imported from elsewhere.

More specifically, knowledge transference based on soil classification principally involves soil management and crop production practices, such as fertilization, tillage, irrigation, crop species selection, and so on. Although it must be noted that, in most cases, only principles and methodologies can be transferred, it should be emphasized that reasonably accurate estimates of the levels of management inputs and crop performance can be made. Examples of management principles include stratagems for phosphorus (P) fertilization in soils with a

high P-fixation capacity, methods of irrigation as they relate to crop phenology, and correction of subsoil acidity. This kind of transferable information is derived from empirical experimentation and induction from the knowledge of the interactions involved among soil characteristics, climatic conditions, crop requirements, and management practices (Kellogg, 1961).

In this context, soil classification mainly facilitates "horizontal transfers"; that is, the transfer of experience from experiment station to experiment station at a scientific level. Since this information is not necessarily directly applicable to farm situations at new locations, it must be adapted to conform to the economic decision environment of the local farmer. The process of adaptation and extension to the farm level may be termed "vertical transfer," and it is a critical element in the international transfer of agrotechnology (Hayami and Ruttan, 1971).

An important question of consequence to agrotechnology transfer is whether there exists sufficient soil and agronomic knowledge in the tropics that can be transferred. At first glance, the answer to this question would seem affirmative. Many countries in the tropics have an impressive history of agricultural research, and a sizable body of relevant knowledge has accumulated over the years. The extent of this research is well documented in various publications, and special reference is made here to "A Review of Soils Research in Tropical Latin America" (Sanchez, 1972), "Soils of the Humid Tropics" (National Research Council, 1972), "Soil Management in Tropical America" (Bornemisza and Alvarado, 1975), a three-volume "Bibliography of Soils of the Tropics" (Orvedal, 1975, 1977, 1978), and the annual reports of the International Agricultural Research Centers. These and other publications indicate that the aggregate of experience with tropical soils is significant. An analysis of the literature, however, shows that the knowledge is distributed unequally among tropical countries, often lacking where it is most needed, and that the experience is also unequally distributed by kind of soil, especially since many experiment stations are located on atypical soils. Consequently, the as yet underutilized land resources remote from population centers in the tropics have been largely neglected.

Moreover, in many instances, the soils on which the agronomic research was conducted are not adequately identified and classified, which severely impedes the extrapolation of research results to other areas. Thus, it must be stressed emphatically that the classification of the soils in an internationally recognized system, in conjunction with soil survey, is a *conditio sine qua non* for the effective transference of the results of agronomic research.

Knowledge gaps are now being partially filled through the work of the 11 International Agricultural Research Centers in Africa, Asia, and Latin America, six of which were established since 1970. In addition, bilateral agricultural assistance programs are underway in many LDCs, and several national gov-

ernments are greatly intensifying their own research efforts. Further, there now exists an operational network of financial institutions, including the World Bank, the Inter-American Development Bank, the Asian Development Bank, the African Development Bank, and various Common Market Banks. In recent years, these institutions have markedly increased their emphasis on agriculture and rural development (Wortman, 1976). For the first time, then, there now exists an institutional and technical infrastructure to fund and conduct the research needed to generate the scientific knowledge base for a productive tropical agriculture.

But the results of this research must also be disseminated; experiment station and extension service capacity in many LDCs, however, remains critically limiting. The establishment of such institutions in these countries is of crucial importance to the successful transfer, adaptation, and application of the knowledge and technology developed elsewhere.

III. SOIL CLASSIFICATION IN PERSPECTIVE

A. Some Needs for Soil Classification

The soil mantle forms a continuum over the earth and is very difficult to study as a whole. Through the systematic subdivision of this whole, however, it is possible to describe many soils and predict their potential and response to management inputs. In a classification scheme, soil bodies are recognized by their properties and identified by names of classes; these soil names, then, provide identity to otherwise unidentified land areas and facilitate communication about features of soils and predictions about their behavior when managed or used in particular ways. Thus, soil classification is necessary for proper use of experience and to extend the results of research.

Each soil is a unique combination of external and internal characteristics, with a defined range of expression that can be observed in the field and studied in the laboratory. These characteristics both describe the history of a soil and predict its potentials. The Soil Survey Manual (Soil Survey Staff, 1951) clearly points out that "the influences on soil behavior of any one characteristic, or of a variation in any one, depends upon the others in the combination."

Soil classification draws on the experience and results from all areas of fundamental and applied soil science, and the products of these areas can only be synthesized for accurate application through soil classification. Experimental field plot techniques deal with soils at small places. Through comparison of sets of data from different places, principles can be developed that fit the facts. Useful results from geographically separated experimental plots occur only when the plots themselves are representative samples of defined kinds of soil. For

interpretation, whether for an understanding of soil or for predictions about its behavior, results must be related to defined soil units. This is a major function of soil classification (Soil Survey Staff, 1951).

A taxonomic classification of soils is a tool to help us organize our knowledge about soils and to remember that knowledge. Classification also enables us to see relationships among and between soils and their environment and to formulate principles of prediction value (Soil Survey Staff, 1951).

The Soil Survey Manual of 1951 summarized many concepts and operational aspects of the Cooperative Soil Survey of the United States. In addition to describing procedures for conducting and publishing soil surveys, the book contains discussions of many concepts of applied soil science. The writers emphasized the importance of accurately predicting soil productivity for making economically valid agricultural and nonagricultural recommendations.

Soil surveys require soil classification, of course, but other disciplines in soil science also require soil classification for appropriate application of results. In addition to classifying soils and plotting their boundaries on a map, a soil survey is able to correlate and predict the suitability of soils for various plants and the expected behavior and productivity of soils under different management systems. Most of these types of interpretations over the years have been based on reasonable estimates of similarity (correlation) rather than on specific experimental research on every defined soil. Because each experimental plot is a sample of a landscape, it should be an accurate and representative sample of a defined kind of soil worthy of being sampled and studied.

The key to success is having defined kinds of soils—thus the urgent need for a classification that is relevant. In any soil classification system, a soil taxon provides a mental image of a collection of soils that are considered similar enough to be treated as one thing for a particular purpose (Cline, 1977). Consequently, the most important function of a taxon is to provide identity and class membership as determined by defined sets of physical, chemical, and biological characteristics.

Every system attempts to provide the largest feasible number and most precise statements for its objective. A classification can best serve only one major objective. Conflicts can easily arise, therefore, in assessing the usefulness of a classification. An apparent conflict exists between an objective for agricultural land use and management on the one hand, and similarity of soils in terms of morphology and genesis on the other.

The most widely accepted concepts and models of soils are based on the development of soil properties. Their relationships to observable landscape features form the basis for soil mapping, and, because of this reliance, systems of classification emphasizing soil morphology have been used by most soil survey organizations.

B. Development of Criteria for Soil Behavior

By 1950, the difficulties in consistently defining and applying the "Great Group/Series" classification system in the United States were considered to be insurmountable, and it was decided to develop a new, more refined, and more practical system of soil classification. Seven approximations over 25 years were produced by the Soil Survey Staff of the Soil Conservation Service of the U.S. Department of Agriculture, in cooperation with pedologists from the United States and abroad. The culmination was the publication of Soil Taxonomy (Soil Survey Staff, 1975), which is already generally regarded as a means to one worldwide system of soil classification.

An important aspect of the development of this system was the need for one or more categories that would group soils by properties relevant for use and management. Categories called "high families" and "low families" were proposed for testing High families dealt with central concepts and intergrades, and low families used properties thought to be significant for use and management for agriculture. The criteria suggested by Kellogg in 1951 (Cline, 1979) to group series into low families were drainage class, texture and coarse fragments, degree of development relative to modal profile, degree of weathering, and size (thickness) of profile relative to modal profile. The testing of high and low families by placing existing soil series into these categories revealed the lack of precise definition of criteria and also of the series themselves (Cline, 1979).

Guy Smith, the principal author of Soil Taxonomy, insisted on classifying cultivated soils to assist in interchanging results of experience throughout the world, in contradiction to the then current emphasis on classifying "virgin" or relatively undisturbed soils. He also noted that if the Soil Survey Staff were to succeed in making each low family a group about which fairly specific management recommendations for given phases could be made, then soil temperature and soil moisture (or substitutes) must be in the system (Cline, 1979).

In the third approximation of the new system, the criteria tested for grouping series into low families were texture below the A horizon, permeability below the A horizon, soil drainage class, moist and dry consistency below the A horizon, and soil depth.

In the fifth approximation, it was hoped that classes of low families would be as nearly uniform as possible in those properties that affect development of roots and the movement and retention of soil moisture. At that time, there were nine classes of mineral soils in the highest category. For seven of those groups, the soil family criteria included available water capacity in the 6- to 60-inch depth, and also in the 60- to 240-inch depth if relevant; permeability to at least 60 inches; consistency, both moist and dry; and presence of toxic substances. In the other two groups, clay mineralogy and base saturation were also used.

Definitions of the criteria and their limits were tested again and again by placing series into the proposed classes. The sixth approximation established the criteria for the category called "family," and the seventh approximation set the trend for family definitions by specifically defining classes in a systematic manner (Cline, 1979).

The evolution of interpretive groupings was not haphazard; rather, it was the product of repeated testing. Data from the United States and other parts of the world (1) provided an expansion of genetic theory and a means of testing the model against the real world, (2) governed the choice of class limits, and (3) served to give an applied bias to the lowest two categories (family and series) by evaluating existing interpretations for those subdivisions.

C. Soil Taxonomy

1. *Categories*

Soil Taxonomy (Soil Survey Staff, 1975) was developed on the premise that a classification which presents a model of genetic relationships among soils is the most effective system for understanding soils as natural bodies. The concept of polypedons was created to insure that the soil bodies we classify are the same bodies we attempt to map.

The definitions of the higher categories are more abstract than those of the lower categories (family and series), yet the features used to satisfy the definitions of all categories are soil properties. The bases for differentiating categories are related to models of genesis (Table I). The recognition of classes within a category vary according to the combination of soil properties thought to best reflect, and be consistent with, the definitions of that category.

The *order* category consists of 10 classes of soils whose features differ according to the degree and kind of dominant sets of soil-forming processes that have existed. Within the order classes, *suborders* are distinguished by soil properties that reflect the major control of current processes; climate, parent material, and biological activity are examples of such control. Within each suborder, *great groups* are defined by soil properties that provide additional influence on current processes not identified in the higher categories.

Great groups are divided into *subgroups* whose properties represent departures from a central concept of the great group. These departures are usually due to intergradation of processes, but some are extragrades, with properties not related to other genetic pedons. Within each subgroup, the *family* classes contain soils having similar physical and chemical properties that affect their responses to management and manipulation for use. The soils in families can be further classed into *series* whose restricted ranges of properties provide further homogeneity of morphology and composition.

Table I
Example of Relationships among Category Subdivisions in Soil Taxonomy

Category name	Basis for differentiation	Example of class name	Main features of the class
Order	Dominant soil process that developed soil	*Ult*isol	Clay accumulation; depletion of bases
Suborder	Major control of current process	Ud*ult*	Soil moist most of me; humid (udic) cli...ate
Great group	Additional control of current process	Trop*udult*	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

2. *Significance of the Soil Family Category*

As is true with all multicategorical systems, the properties associated with classes accumulate from the higher and more abstract categories down to the lower categories. Thus, many more statements can be made about soils in a family than about the soils in a suborder. In addition, in contrast to the many genesis-related properties used at higher levels, the soil family category in Soil Taxonomy is based on properties without regard to their significance as marks of soil processes or the lack of them (Soil Survey Staff, 1975). The responses to management of comparable phases of all soils in a family are thought to be nearly enough the same to meet most needs for practical interpretations of such responses. For this reason, families are defined primarily to provide groupings with restricted ranges in particle-size distribution in horizons of major biological activity below plow depth, mineralogy of these same horizons, temperature regime, thickness of soil penetrable by roots, and a few other properties to provide additional homogeneity in some families, as shown in Table II for one specific subgroup.

Eleven *particle-size classes* are commonly used; however, 40 additional contrasting particle-size combinations are recognized to identify changes in pore-size distributions that seriously affect movement and retention of water. Seventeen classes of *mineralogy* are recognized to assist in evaluating the presence of toxic

Table II
Currently Recognized Families in the United States of a Selected Subgroup, Typic Paleudults[a]

Family characteristics		
Particle-size class[b]	Mineralogy[b]	Soil temperature[c]
Loamy-skeletal	Siliceous	Mesic
Loamy-skeletal	Siliceous	Thermic
Loamy-skeletal over clayey	Siliceous	Mesic
Clayey-skeletal	Mixed	Mesic
Coarse-loamy	Siliceous	Hyperthermic
Coarse-loamy	Siliceous	Mesic
Coarse-loamy	Siliceous	Thermic
Fine-loamy	Siliceous	Mesic
Fine-loamy	Siliceous	Thermic
Fine-silty	Siliceous	Thermic
Clayey	Kaolinitic	Mesic
Clayey	Kaolinitic	Thermic
Clayey	Mixed	Isohyperthermic
Clayey	Mixed	Mesic
Clayey	Mixed	Thermic
Clayey	Oxidic	Isohyperthermic

[a] Paleudults have thick zones of clay accumulation and only modest reserves of weatherable minerals. Typic subgroups are well-drained soils.

[b] The control section for both particle size and mineralogy is the upper 50 cm of the zone of clay accumulation (argillic horizon).

[c] Soil temperature is measured at a depth of 50 cm from the soil surface.

materials and degrees of weathering that influence chemical or physical behavior. Eight classes of *soil temperature* are recognized in the family category, providing such information if not stated or implied at higher categorical levels for a particular soil.

Use of family taxa rather than series taxa for identifying polypedons can affect the precision of interpretations, but if the nature of the soil or the state of knowledge is such that precise interpretation for a wide range of uses is impossible or not needed, then little is lost by naming soils as phases of families rather than as phases of series.

3. *The Future of Soil Taxonomy*

It seems obvious that when a system employs available information and cumulative experience, a classification can be devised that organizes and arranges the data in a desired manner. Because Soil Taxonomy was based on and evolved from knowledge and experience with soils in the United States, the placement of those soils and predictions of their behavior have been very accept-

able. Class limits were tested and modified by examination of the data base available in the United States at the time, and the physical and chemical properties and estimated crop yields under several levels of management were repeatedly considered. A global soil-data base and worldwide experiences were not extensively tested for Soil Taxonomy, however, partly because the main emphasis was the need to classify soils in the United States and partly because of the lack of familiarity with the existing world data base.

In the United States, there are only a few areas on which to develop criteria for tropical soils. As scientists in the tropics and subtropics began to evaluate Soil Taxonomy by attempting to fit their soil information into the system, it became apparent that definitions and class limits similar to those used for soils of the United States did not provide satisfactory groupings for the broad range of soils and conditions in the tropics. Soil-moisture regimes and some ranges of soil temperature, for instance, may need refinement and modification to provide useful separations or groupings. The importance of translocated clay in understanding the slightly weathered soils of the temperate regions tends to be far less significant in the highly weathered soils of the tropics.

In addition, different methods for determining available water, cation-exchange capacity, and extractable ions often reflect past experience and training and vary in standards across the world. Moreover lack of correlation among laboratory values makes consensus about criteria difficult, even when there is a desire for standardization and uniformity.

Thus, what may appear to some observers to be a deficient classification system is merely a reflection of the stage of its development. As the data base and experiences throughout the world, particularly in the tropics, become available and can easily be shared, compared, and tested, the same kinds of changes associated with the early development of Soil Taxonomy will occur frequently until there is available a more complete and precise data base on soils of the lower latitudes.

D. Taxonomy and Agrotechnology Transfer

The concept of agrotechnology transfer involves at least two aspects if the transfer is to be successful. The first is research data about soil behavior or response when used for a particular crop or farming system with a specified set of management practices. The work must be done on a representative sample of a defined soil, otherwise the places where transfer could possibly occur are unknown. These predictions depend upon conscientiously designed experiments conducted by competent researchers. The second deals with the economic, social, and political conditions against which to evaluate the experimental results in order to provide recommendations.

Predictions of soil-crop responses are transferable to the extent that site- or

location-specific influences are quantified and understood. Soils record a long and complex history, and it is entirely possible that two soils may have followed two different pathways but now may have the same set of properties used to identify taxa. Soils may also exhibit features of agronomic significance that are *not* used to identify soil taxa. For instance, general predictions can be made about a soil's behavior related to its internal composition, but crop repsonse may vary in any year because of the marked influence of locational factors, such as solar radiation, precipitation, and pests that respond to the uniqueness of a particular season at a particular site. These latter items usually are not transferable and must be measured and evaluated throughout a decentralized system if effective agrotechnology transfer is to take place. Thus, the shape of response curves at different sites may be reasonably predicted (see Section V), but the magnitude of the response may depend on conditions that occur at a given location during a given growing season.

Tillage problems, erosion hazards, commonly adapted crops, potential hazards from naturally occurring toxic compounds, and general nutrient supply can often be estimated for soils classified in higher level taxa. If crop responses to management inputs on particular kinds of soils can be predicted for lower level taxa, then it is clear that many other types of information can also be transferred among soil taxa.

Agronomic experiments are usually replicated by treatment but seldom by kind of soil because of an assumed similarity of predicted response for similar soils. Results from experiments conducted on the same phases of the same kinds of soils can be evaluated for their correlation with common soil properties. If these experiments are conducted on the same kinds of soils but at different locations, then site-specific conditions can also be evaluated and predictions of crop responses can be improved. Agronomic interpretations vary in their specificity, just as taxa within Soil Taxonomy differ in their specificity.

As additional precision and accuracy are desired, similarity of all inputs at each site must be increased, otherwise the predictions cannot be improved. They will be limited by the degrees of similarity of inputs. A crucial input is proper identification and classification of the soil in which the cropping experiments are conducted.

IV. AGROTECHNOLOGY TRANSFERENCE RESEARCH

A. The Benchmark Soils Project

1. Rationale

As pointed out in Section II, it has long been assumed that an adequate system of soil classification provides a suitable vehicle for the extrapolation of soil-

related experience. Nonetheless, this basic assumption has never been subjected to the scrutiny of field experimentation, neither in temperate nor tropical areas.

In an attempt to determine scientifically the transferability of agroproduction technology in the tropics on the basis of soil taxonomic units, the Universities of Hawaii and Puerto Rico have established companion projects under contracts with the U.S. Agency for International Development. The parallel projects were implemented in 1974 and 1975, respectively, and are commonly referred to as the Benchmark Soils Project. The term "benchmark soils" was drawn from and conforms to the concept originally advanced by Kellogg (1961). The project is briefly described here to present an example of agrotechnology transference research.

The primary objective of the Benchmark Soils Project is to demonstrate that and how soil management and crop production knowledge can be transferred among tropical and subtropical countries, using soil family taxa as a point of reference. The central tenet of the project is that the soil family, as defined in Soil Taxonomy (Soil Survey Staff, 1975) and discussed in Section III, affords a sound basis for agrotechnology transfers. This hypothesis derives substance from the fact that soil families are narrowly defined taxa that have been contrived for the explicit purpose of providing groupings of soils that are reasonably homogeneous in characteristics important to the growth of plants. Soils belonging to the same family, therefore, should have essentially the same management requirements, analogous responses to soil manipulation, and similar potentials for crop production. The soil family thus stratifies the population of soils into pragmatic units that, through the differentiae which define them, have the inherent attribute to facilitate agrotechnology transfers.

Knowledge transfers can be made at any categoric level of taxonomic system, with increasingly precise statements possible at lower levels. Since predictions and transfers of crop performance and soil management could be refined if they were based on information more specific than that contained in soil family taxa, an argument could be made in favor of using the lowest category of Soil Taxonomy, the soil series, as the basis for agrotechnology transfers. In addition, one could also use phases to indicate soil characteristics that are not considered in taxa definitions but are important to a specific land use.

It is well to remember in this context that the differentiae used for series are mostly the same as those used for the classes in other categories to which the series belongs, but the range permitted is less than is permitted in the family or some other higher category. Taken collectively, however, the number of possible distinctions is too large to be comprehended readily and to be incorporated in a key (Soil Survey Staff, 1975). Phases, on the other hand, provide for a utilitarian classification that can be superimposed on the taxonomy at any categoric level to permit more precise interpretations and predictions. The purpose of phases, like that of soil series, is mainly practical, and no strict rules for their usage have been established.

Thus, although the most precise predictions can be made for phases of soil series, it would clearly be unrealistic to use this category in the process of international agrotechnology transfers. First, such detailed information rarely exists for LDCs; second, soil series and phases are not rigidly defined, and different rationales for establishing them are employed in different countries. As a consequence, the lowest categoric level of Soil Taxonomy that can be universally applied in a uniform and consistent manner is that of the soil family.

2. *Experimental Methodology*

In order to verify the transferability of agrotechnology, a test crop must be grown under similar management conditions on the same soil family in a network of sites. Because members of a soil family are not identical, but similar within a range of characteristics, the outcomes should be expected to vary within a similar narrow range.

Three soil families from upland areas of the tropics that have the potential to be productive under appropriate management practices were selected by the Benchmark Soils Project to test the transfer hypothesis. The first family selected was the thixotropic, isothermic family of Hydric Dystrandepts, which is derived from volcanic ash, and sites have been established in Indonesia, Hawaii, and the Philippines. The clayey, kaolinitic, isohyperthermic family of Tropeptic Eutrustox, which links the Puerto Rico and Hawaii projects, was the second family selected, and sites have been established in Brazil, Hawaii, and Puerto Rico. The clayey, kaolinitic, isohyperthermic family of Typic Paleudults was included at the request of the participating cooperating countries because it is an important, underutilized soil in the tropics, and sites have been established in Cameroon, Indonesia, and the Philippines. The locations of the soil networks are shown in Fig. 1. The soils are described in Technical Report 1 and Technical Report 5 (Ikawa, 1979; Beinroth, 1979).

The research design and methodology to test the transfer hypotheses were developed at the Workshop on Experimental Designs for Predicting Crop Productivity with Environmental and Economic Inputs (Silva and Beinroth, 1975). In the project design, distinction is made between two types of experimental sites, designated primary and secondary sites. Primary sites of about 8 ha are locations where three kinds of experiments, transfer, variety, and management experiments, are conducted, whereas secondary sites of about 2 ha are locations where only transfer experiments are conducted. Secondary sites may differ from primary sites in that they exhibit variations in soil properties important to plant growth, such as base saturation or particle size, within the range permitted by the definition of the soil family. A minimum of eight sites was established for each soil family network.

The transfer experiments (N × P experiments) are designed to provide data to

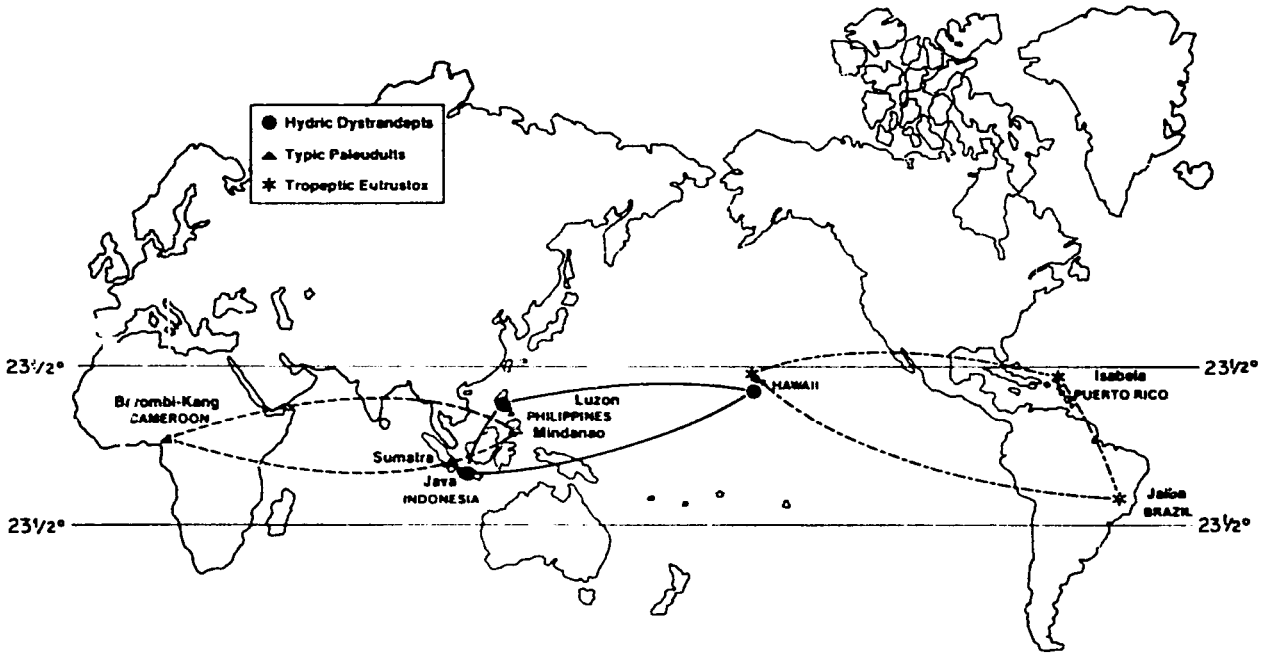

FIG. 1. Location of the experiment sites on the three tropical soil families studied in the Benchmark Soils Project.

test the hypothesis of transferability. The variety experiments are intended to evaluate varieties of maize, the test crop, for both their suitability to the environment and their responsiveness to N and P. And the management experiments are designed to provide information to local government agencies on ways to increase resource productivity by appropriate land use at different levels of management.

In the transfer experiments, the variables to test the transfer hypothesis were selected because they are (1) controllable, (2) important to the test plant, maize, and (3) key features of the soil families under study. Phosphorus (P) was selected because it is an important limiting factor to crop yields and is linked with the definition of the three soil families under study, since technical information contained in the soil family name indicates the presence of mineral constituents that determine the soil's ability to "fix" P. Thus, the term "thixotropic" connotes mineral constituents with a high capacity to absorb and immobilize fertilizer P. Similarly, the term "clayey" indicates soils with finely divided particles that possess large surface areas. In addition, the affinity of such an extensive surface for P is implied by the suffixes "ox" in Eutrustox and "ult" in Paleudult. Nitrogen (N) was selected as the second variable because it is rapidly depleted in tropical soils when the land is cleared and continuously cropped, and it is often the most limiting nutrient to crop growth in the tropics. It also plays an important role in the utilization of fertilizer P by crops and influences the yield level attained.

The treatment design selected was the 5^2 partial factorial modification by Escobar described by Laird and Turrent (1979). It provides 5 levels each of the 2 variables combined, to give 13 of the 25 possible treatment combinations. It was found to be one of the outstanding designs on the basis of (1) appropriateness for use in graphic estimation of economic optima, (2) magnitude of bias error, (3) number of treatment combinations, and (4) magnitude of variance error. It also has good coverage of the factor space with its 13 treatments. A diagram of this design is shown in Fig. 2 and coded values for the treatments are given in Table III. The same treatment combinations are used for all three families, but the rates used differ among families according to the different levels of these nutrients in the different soils. These treatments are replicated three or four times and installed in a randomized complete block design.

The experiments have been designed so that all other controllable factors such as irrigation, other nutrients, plant protection, and plant density are maintained near optimum levels for clarity of treatment effects. Field operations, data collection, and data processing follow standardized procedures and guidelines to assure comparability of results throughout the network.

Weather variables, disease incidence, and crop variety adaptions are not reflected in the soil family names, although predictions for crop response need to incorporate these data. Therefore, weather variables such as temperature, rain-

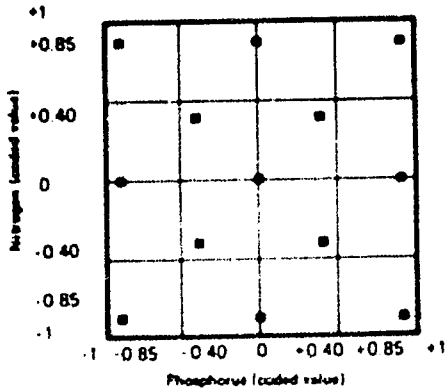

Fig. 2. Treatment design for 5^2 partial factorial modification by Escobar used for the two-factor transfer experiments

fall, relative humidity, solar radiation, and wind speed and direction are measured at each experimental site. Experimental grain yield results, with all related data on controlled and uncontrolled variables, are analyzed by project personnel, in conjunction with the project statistical consultants, with the ultimate objective of testing the transfer hypothesis and developing a model of agrotechnology

Table III
Coded Values of Treatments Used in Transfer Experiments

Treatment	Phosphorus	Nitrogen
A	-0.85	-0.85
B	-0.85	+0.85
C	+0.85	-0.85
D	+0.85	+0.85
E	-0.40	-0.40
F	-0.40	+0.40
G	+0.40	-0.40
H	+0.40	+0.40
J	0[a]	0
K	-0.85	0
L	+0.85	0
M	0	-0.85
N	0	+0.85
O	Complete control[b]	
P	Partial control[c]	

[a] 0 = optimum treatment, includes micronutrients
[b] Complete control = no fertilizer applied
[c] Partial control = no treatment variables applied but given blanket application of macro- and micronutrients.

transfer based on soil interpretation and soil classification. A discussion of the unique test of the transfer hypothesis is presented in Section V.

The results of a total of 78 transfer experiments conducted by the project on three different soil families clearly support the general validity of the transfer hypothesis. The general shape of the response surface is similar among members of the same family (see Fig. 5), but differences are apparent due to variations in soil characteristics within the limits of the soil family and soil N and P levels. The magnitude of the yield response likewise varies due to the individual site response-input relationship, which is affected by the specific environment of the site during the growing period. Nonetheless, there are general trends predictable across all sites of each soil family network.

The common and specific behavior from all soils comprised in a soil family was further substantiated by the kind of response, or length thereof to individual fertility variables. For example, no consistent response to lime on the Hydric Dystrandepts or to K on the Tropeptic Eutrustox was found over all sites. In addition, downy mildew disease occurred at very low levels (<1%), if at all, on Hydric Dystrandept sites even with susceptible varieties. It is believed the isothermic temperature regime [cool (15-22°C) and wet] is unfavorable for growth of the organism. The research also confirmed the different potential of the three soil families for maize production.

Particulars and results of the various kinds of experiments are contained in Progress Reports 1 and 2 (Benchmark Soils Project, 1978 and 1979).

B. Developing Transferable Agrotechnology

The development of sound management practices that can be transferred is essential for increasing crop production and for wise land utilization. Experimentation to identify these practices can be costly and time consuming; however, the indication that agrotechnology can be transferred on the basis of the soil family offers an approach to reduce greatly the cost and time to acquire this knowledge. The key requirement is that the soils of research centers in the tropics, as well as those of important agricultural areas, be classified according to Soil Taxonomy. Management information developed at research centers throughout the tropics can then be transferred, economically and efficiently, to the appropriate soil families in agricultural areas of the tropics. It is likely, however, that not all management practices will be available for all soils or crops of interest in a particular country. In this case, the desired management practices can be developed on benchmark soils representing important agricultural areas of a country or a region.

The basic objectives of the research to be conducted on carefully selected benchmark soils should be to (1) develop management practices that allow

sustained crop production conducive to maximum yields for differen' levels of economic inputs without causing soil degradation, and (2) quantify the soil/land qualities of benchmark soils in relation to the needs and performance of important crops. The latter necessitates knowledge of the soil requirements of specific crops and is aimed at providing a better basis for soil survey interpretation, land evaluation, and extrapolation of research results.

The particular kind of research needed will vary with the nature of the problems associated with a particular benchmark soil, the crops to be grown, and the prevailing socioeconomic considerations. Soil-related constraints to crop production likely to be encountered and requiring investigation include the areas of soil fertility and plant nutrition, soil amendments, plant adaption, soil-water management, soil biology, soil erosion and conservation, and soil survey interpretation and land evaluation. Swindale (1979) has recently scrutinized the research needs on these and other aspects of tropical soils and reference is made to his paper. The Technical Advisory Committee (TAC) to the Consultative Group on International Agricultural Research (CGIAR) also has endorsed the use of benchmark soils sites and the need for soil, plant, and water studies upon them (TAC Secretariat, 1979).

It is clearly impossible to conduct extensive research on all soil families. It may also be unnecessary. Different soil families differ in some, but not in all, respects; thus, we may assume that soils from different soil families will perform alike in some ways if they possess qualities common to, and crucial for, a particular type of land use. The sphere of transferability of knowledge and experience, therefore, is not restricted to members of the same soil family but extends to all families that possess qualities common to a particular use requirement. This commonality of soil qualities defines the sphere of transferability for a particular soil use. Since the sphere of transferability transcends soil family boundaries, the identification of the cause-and-effect relationships between soil characteristics or qualities and crop performance is essential to the wide, practical application of agrotechnology among soil families.

V. QUANTITATIVE VERIFICATION OF TRANSFERABILITY WITHIN A SOIL FAMILY

A. General

Transferability of management practices may be accepted when the weight of evidence is sufficiently convincing. Based on data from a series of experiments conducted by the Benchmark Soils Project, where the management factors are the same for each experiment, the feasibility of transferring crop response was

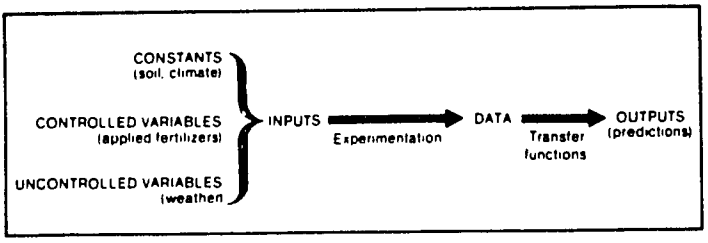

Fig. 3. The schematic approach to testing the transfer hypothesis; sequence of steps required to implement the experimental design of the Benchmark Soils Project.

evaluated. Developed in this section are the criteria and the data analysis methodology needed for the verification of transferability within a soil family.

Quantitative verification starts with formulation of a general transfer model for the relationship between response data and various inputs, as is schematically shown in Fig. 3. Two determinants of yield, soil and the covariant of long-term climate, are important inputs and assumed to be constant within a soil family. Designed as variable inputs are management factors, for example, applied fertility, which are intentionally controlled at several levels. Other controllable factors not part of the treatment design are experimentally maintained at a constant level so that the response to the treatment design factors is the only information to be transferred. Actual soil levels of the treatment design factors are not constant across the experimental sites within a soil family, however, due to natural and past management variabilities. These and other variable inputs, including weather factors such as temperature and solar radiation, cannot be controlled at a constant level, but they can be measured at each site.

B. The Transfer Model

For developing a measure of the weight of evidence in order to evaluate transferability, the relationship between the response data and the known levels of controlled and uncontrolled variables is characterized by parameters of a transfer function equation. Neglecting the uncontrolled variables for now, we can express the observed plot data (Y), which depend on the controlled variables, for example, applied phosphorus (P) and applied nitrogen (N), as

$$Y = f(\mathrm{P}, \mathrm{N}) + E \tag{1}$$

where the error component E, the difference between the response data Y and the transfer function $f(\mathrm{P}, \mathrm{N})$, is attributable to unknown sources and assumed to be random variation. Different mathematical forms for $f(\mathrm{P}, \mathrm{N})$, including polynomials and exponentials, have been used by soil fertility specialists. Historically,

the parameters of the response-input relationship, $f(P, N)$, are estimated from the data for each site and the estimated function, $\hat{f}(P, N)$, is constructed by substituting the calculated statistics for the parameters. The resulting prediction equation for each site is expressed as $\hat{Y} = \hat{f}(P, N)$ where the $\hat{Y}$s are the predicted data for each plot. The differences between the observed plot data and the predicted data, $Y - \hat{Y}$, are called the ordinary residuals.

Agrotechnology transfer is the extrapolation of a response-input relationship, estimated from a series of experiments, to new sites. Practically, we would like to evaluate transferability with only one series of experiments; consequently, the evaluation needs to simulate the transfer to nonexperimental sites. As developed by Wood and Cady (1980), one approach is to predict yields, denoted as $\hat{Y}_{i(i)}$, for one of k experimental sites using a transfer function estimated from the other $(k - 1)$ sites. The subscript i is an index for sites, $i = 1, 2, \ldots, k$. This is then repeated for each of the k sites, that is, we predict yields for each site based on a transfer function estimated from the other $(k - 1)$ sites. If the *transfer* residuals, $Y_i - \hat{Y}_{i(i)}$, are approximately the same magnitude as the *ordinary* residuals, $Y_i - \hat{Y}_i$, calculated by fitting a response function individually to each of the k sites, we have evidence for agrotechnology transfer. A specific criterion for the evaluation is the prediction statistic P, defined as the ratio of the pooled sum of squared transfer residuals to the pooled sum of squared within-site ordinary residuals. Thus,

$$P = \sum_{i=1}^{k} (Y_i - \hat{Y}_{i(i)})^2 \Big/ \sum_{i=1}^{k} (Y_i - \hat{Y}_i)^2 \qquad (2)$$

Two transfer function models will be considered.

1. Transfer Model 1. Assuming the data can be adequately fitted by a quadratic polynomial in the design variables, a simple transfer model (transfer model 1) is a second-order polynomial response surface that is common to all sites but that allows a different intercept for each site. For this model, the test statistic $P - 1$, multiplied by a known constant, follows the F distribution with $5(k - 1)$ and the pooled residual degrees of freedom (df). The prediction statistic P is evaluating the adequacy of a model with design variables only for use as a transfer model. The prediction equation is based on the shape of the response surface estimated from the other sites coupled with the site mean. Algebraically,

$$\hat{Y} = b_{0i} + b_1P + b_2N + b_3P^2 + b_4N^2 + b_5PN \text{ (Model 1)} \qquad (3)$$

If the P and N variables are coded around zero, then the site intercepts are the predicted yields in the middle of the design. The i subscript on b_{0i} indicates that the intercepts can vary from site to site, while the $b_1, b_2, \ldots, b_5$ terms determine the common shape of the response surfaces. For determining the economically optimal combination of P and N, only the shape, not the height, of the

response surface is important. Consequently, differences in the average heights of the individual site response surfaces are allowed in the transfer model by centering the observed yields about the mean for each site.

2. Transfer Model 2. A second transfer model (transfer model 2) is model 1 augmented by additional variables for the uncontrolled but measured site variables. These additional variables account for differences in the shape of individual site response surfaces due to interactions between the response surface variables and the site variables, for example, between the P and N linear terms and site variables. For one site variable, denoted by p, the estimated transfer function is written as

$$\hat{Y} = b_{0i} + b_1\mathrm{P} + b_2\mathrm{N} + b_3\mathrm{P}^2 + b_4\mathrm{N}^2 + b_5\mathrm{PN} + b_6p\mathrm{P} + b_7p\mathrm{N} \quad (4a)$$

An alternative expression is

$$\hat{Y} = b_{0i} + (b_1 + b_6p)\mathrm{P} + (b_2 + b_7p)\mathrm{N} + b_3\mathrm{P}^2 + b_4\mathrm{N}^2 + b_5\mathrm{PN} \quad (4b)$$

This last equation emphasizes that the interaction variables allow different shapes of the response surface for each site since the estimated coefficients for P and N now depend on p. For transfer model 2, the test statistic, $P - 1$, is no longer proportional to an F statistic, but the distribution and subsequent significance level can be evaluated by procedures given in Wood and Cady (1980).

C. Application of Transfer Verification Methodology

Data from eight maize experiments on the thixotropic, isothermic family of Hydric Dystrandepts were used as a numerical example for testing the transfer of yield response to applied P and N. Included are four sites (IOLE-E, KUK-A, KUK-C, and KUK-D) in Hawaii, two (PUC-K and BUR-B) in the Philippines, and two (PLP-G and LPH-E) in Indonesia. A general description of the experimental and treatment designs is given in Section IV.

A quadratic polynomial in the two treatment variables

$$\hat{f}(\mathrm{P}, \mathrm{N}) = \hat{Y}_i = b_{0i} + b_{1i}\mathrm{P} + b_{2i}\mathrm{N} + b_{3i}\mathrm{P}^2 + b_{4i}\mathrm{N}^2 + b_{5i}\mathrm{PN} \quad (5)$$

is the assumed $f(\mathrm{P}, \mathrm{N})$ and is calculated for each site. The i subscript is an index for site identification, $i = 1$(IOLE-E), 2(KUK-A), . . . , 8(LPH-E); $\hat{Y}_i$ are the predicted yields for the ith site, and the b's are the estimated quadratic polynomial response surface parameters. The six-parameter quadratic polynomial function is fitted well by the data (3 replications of 13 treatment combinations of P and N). Lack-of-fit terms for each site with seven (13 − 6) df are not important and have been pooled with the experimental error sums of squares.

As shown in the previous section, the adequacy of transfer model 1 can be tested by the prediction statistic, which follows the F distribution with 35 and

264 *df*. The calculated F is 2.99, and the probability of a value of this magnitude, on chance alone, is less than 0.01. Based on the weight of evidence of transfer model 1, a model with only design variables will not be sufficient. Stated differently, interactions between sites and the quadratic polynomial variables exist. Additional data analysis shows that the P, N, and P^2 terms of transfer model 1 interact with sites—that is, the eight b_1 coefficients for P, the eight b_2 coefficients for N, and the eight b_3 coefficients for P^2 have a systematic trend over the sites rather than the random pattern expected with no interaction. Consequently, the uncontrolled but measured site variables are introduced to describe the sites quantitatively.

Insight on interactions between treatment design variables and site variables can be gained from plotting the estimated coefficients for P, N, and P^2 against selected site variables as shown in Fig. 4. Block A shows b_1 vs. soil phosphorus as measured by the modified Truog method, Truog P; block B shows b_2 vs soil nitrogen extracted by 2 *N* KCl, extr. N; block C shows b_2 vs the average daily minimum temperature during an 8-week period around 50% tasseling, min. temp.; and block D shows b_3 vs. min. temp.

The systematic trends in the four plots of Fig. 4 reflect the presence of interactions. Estimated regression coefficients calculated by fitting a quadratic polynomial to the data in Fig. 4A are identical to the coefficients obtained by adding two interaction variables to the transfer model

$$\hat{Y} = b_{0i} + b_1\mathrm{P} + b_2\mathrm{N} + b_3\mathrm{P}^2 + b_4\mathrm{N}^2 + b_5\mathrm{NP} + b_6p\mathrm{P} + b_7p^2\mathrm{P} \quad (6a)$$

or, alternatively,

$$\hat{Y} = b_{0i} + (b_1 + b_6p + b_7p^2)\mathrm{P} + b_2\mathrm{N} + b_3\mathrm{P}^2 + b_4\mathrm{N}^2 + b_5\mathrm{NP} \quad (6b)$$

The latter equation shows the effect of Truog phosphorus (p) on the shape of the response surface and, in particular, the effect of a site's level of soil phosphorus on the linear response to applied phosphorus (P) for that site. Table IV compares the P response coefficients, estimated by $b_1 + b_6p + b_7p^2$ of the augmented transfer model (first column), with the P response coefficients, b_{1i}, estimated from the individual site analyses (second column) and from transfer model 1 (third column). The closeness of the first two columns, compared with the third column, indicates the need for site variable data to explain the differences in the P response data.

Based on Fig. 4 and on other analyses, four additional interaction variables were added to transfer model 2, namely, extr. N by N, min. temp. by N, (min. temp.)^2 by N, and min. temp. by P^2. Inclusion of these interactions allows the N and P^2 coefficients of transfer model 1 to vary from site to site. With the six interactions incorporated in the transfer model, the transfer sums of squares were calculated and are shown in Table V along with the ordinary residual sums of

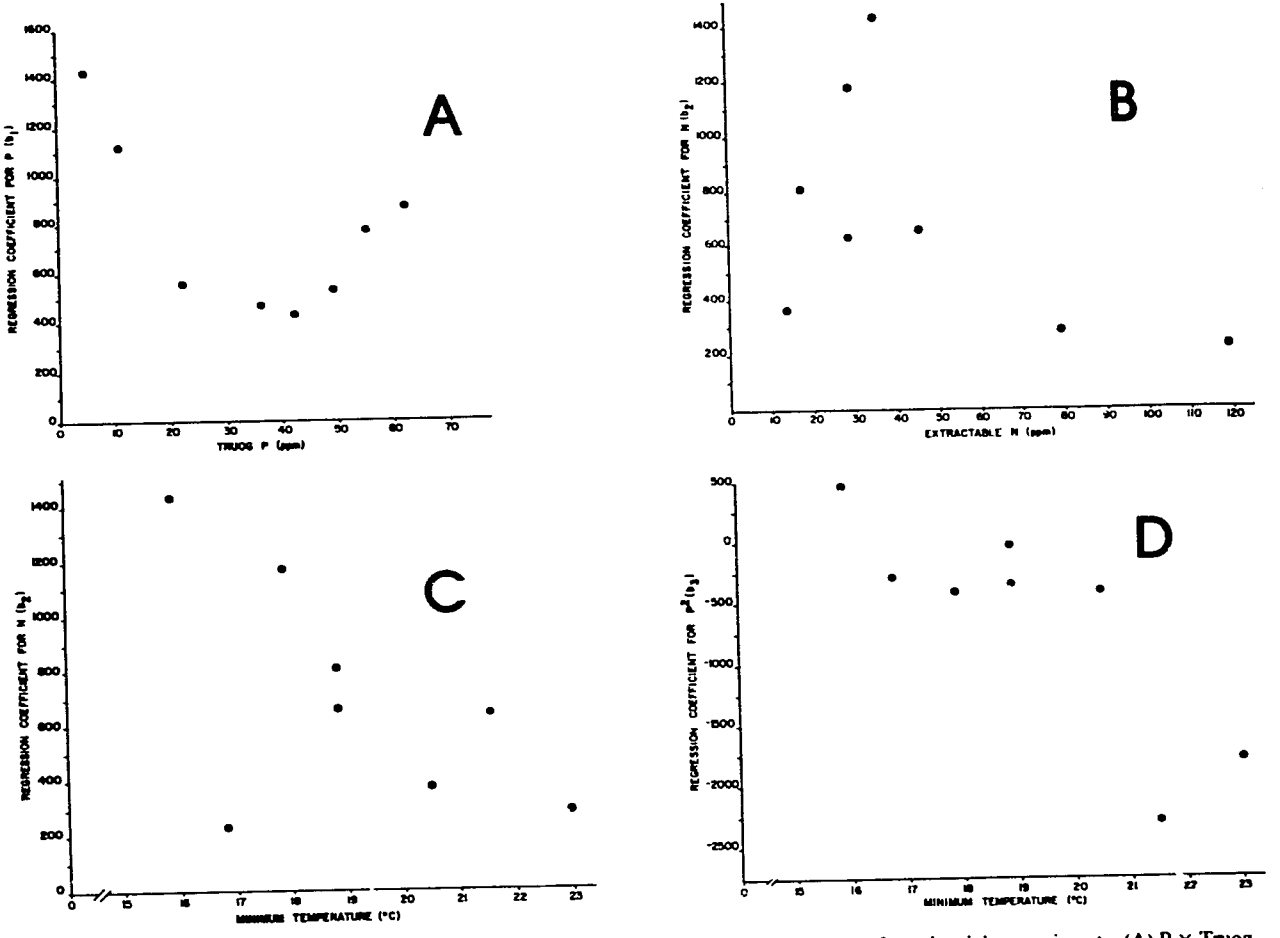

FIG. 4. Relationship between regression coefficients for N and P and individual site variables from the eight experiments. (A) P × Truog P; (B) N × extractable N; (C) N × minimum temperature; (D) P^2 × minimum temperature.

Table IV
Comparison of Regression Coefficients for P Response, with and without Site Variables

Site	P response, site variables added ($b_1 + b_6p + b_7p^2$), Transfer model 2	P response, no site variables (b_1)	
		Individual site model	Transfer model 1
Hawaii			
IOLE-E	447	443	822
KUK-A	634	479	780
KUK-C	546	535	914
KUK-D	1110	890	762
Philippines			
PUC-K	1068	1107	732
BUR-B	1336	1430	685
Indonesia			
PLP-G	418	462	824
LPH-E	691	554	811

squares and the site variable data. For example, when transfer model 2 is estimated from the last seven sites and used to predict the yields for IOLE-E, the transfer sum of squares, $\Sigma(Y_i - \hat{Y}_{(-i)})^2$ is equal to 10,650,460, a 25% increase over the IOLE-E residual sum of squares. Summed over the eight sites, the

Table V
Comparison of Residual and Transfer Sums of Squares after Adding Site Variables (Transfer Model 2)

Site	Residual sums of squares	Transfer sums of squares	Site variables		
			Modified Truog P (ppm)	Extr. N (ppm)	Min. temp. (°C)
Hawaii					
IOLE-E	8,550,008	10,650,460	42	17	18.9
KUK-A	25,714,266	34,309,230	54	13	20.5
KUK-C	13,602,424	15,412,100	49	46	18.9
KUK-D	25,599,726	30,825,610	62	29	17.9
Philippines					
PUC-K	5,869,074	9,035,600	11	79	23.0
BUR-B	25,055,225	32,219,560	5	29	21.5
Indonesia					
PLP-G	29,893,412	40,316,440	36	35	15.9
LPH-E	17,880,236	30,916,190	22	119	16.8
Total	152,164,299	203,685,190			

prediction statistic is

$$P = 203{,}685{,}190/152{,}164{,}299 = 1.34 \tag{7}$$

This value of P is associated with a significance level of 0.32, giving evidence that the response surface for applied P and applied N can be transferred with an estimated transfer model including different intercepts and interactions between the site variables and the treatment design variables.

The P statistic, a ratio of sums of squares, is a summary statistic for comparing the transfer ($Y_i - \hat{Y}_{(-i)}$) and ordinary ($Y_i - \hat{Y}_i$) residuals. The actual magnitudes of the differences between the ordinary $\hat{Y}_i$, based on the individual site data, and the transfer $\hat{Y}_{(-i)}$, based on data from the other sites, are given in Table VI. The tabular values are absolute differences, $\hat{Y}_i - \hat{Y}_{(-i)}$, for five treatment combinations with increasing levels of both P and N, and are averaged over the three replications for each site. The differences display variability but are sufficiently small, especially at the middle levels, so that the transfer predictions, $\hat{Y}_{(-i)}$, could be used for practical purposes to predict response to P and N application for sites where an experiment had not been carried out.

The predicted yields for each site, plotted three-dimensionally with P and N as the horizontal axes, form an estimated response surface showing the predicted yield response for any combination of P and N within the experimental ranges of the factors. The response surface plots in Fig. 5 summarize the results of the transfer analysis. Specifically, both transfer models can be graphically compared with the individual site predictions. In the middle row, the predicted yields (the

Table VI
Absolute Differences (kg/ha) between $\hat{Y}_i$ and $\hat{Y}_{(-i)}$ Using Transfer Model 2 for Five Treatment Combinations of Applied Phosphorus (P) and Nitrogen (N)

	Coded P and N treatment				
Site	−0.85 P/ −0.85 N	−0.40 P/ −0.40 N	0/ 0	+0.40 P/ +0.40 N	+0.85 P/ +0.85 N
Hawaii					
IOLE-E	164	78	59	94	195
KUK-A	684	193	538	469	99
KUK-C	246	183	267	71	481
KUK-D	471	139	350	249	238
Philippines					
PUC-K	160	279	120	78	344
BUR-B	125	225	359	327	93
Indonesia					
PLP-G	561	340	92	276	748
LPH-E	703	582	277	213	985

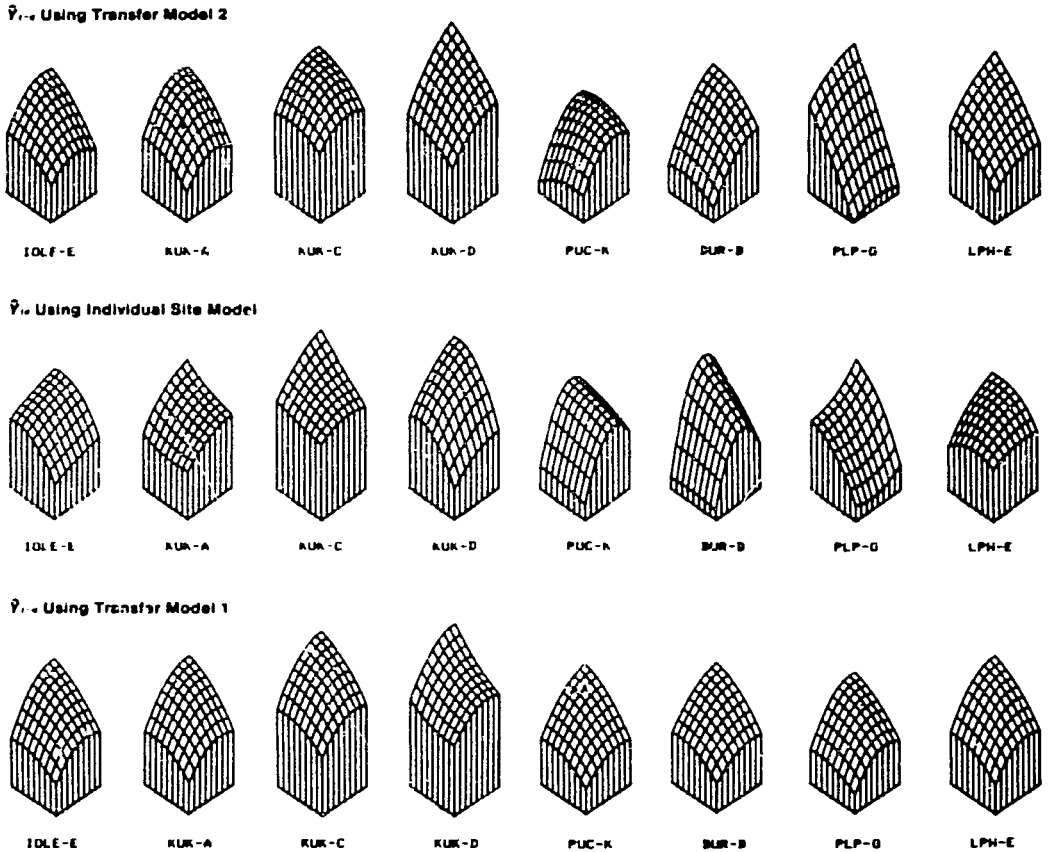

FIG. 5. Comparison of response surfaces of predicted value of the eight experiments for three different models: individual site model (center), transfer model 1 (bottom), and transfer model 2 (top).

vertical axis) from fitting a quadratic polynomial in applied P (the right horizontal axis) and applied N (the left horizontal axis) to each site individually are plotted. The best-fitting response surface is formed from the predicted yields and is represented by the 9 × 9 grid for each site.

To simulate the transfer of technology, consider for a moment that an experiment was not done at the PUC-K site and one wanted to predict the nature of the response surface from the other seven sites. Using transfer model 1, the predicted response surface would be the PUC-K plot in the bottom row, while the plot in the top row results from estimating transfer model 2 from the other seven sites. The top response surface is a closer approximation to the middle response surface than the bottom one for PUC-K and is generally true for all the sites.

The $\hat{Y}_i - \hat{Y}_{i-1}$ differences in Table VI are the differences between the transfer model 2 response surface in the top row and the response surface below in the middle row for five P and N combinations. The P and N combination of −0.85 and −0.85 is the front corner of each plot, the combination of +0.85 and +0.85 is in the back corner, and the other three points are on the diagonal line between the two corners.

If one views across the eight response surfaces in the bottom row, the similarity of P and N response can be noticed, but the resulting transfer equations do not predict as well as the transfer equations from transfer model 2 as represented by the top row. Some of the commonality of the P and N response is retained, but the introduction of site-variable information into transfer model 2 allows each response surface in the top row to have a uniqueness that is associated with the particular site to be predicted. For the P response, the closeness of transfer model 2 to the actual response is also shown in Table IV. For both the P and N responses, (1) the resemblance between the response surfaces for the top and middle rows of Fig. 5 and (2) the P statistic value of 1.34 with the associated significance level of 0.32 for transfer model 2 are weights of evidence that the P and N responses can be transferred.

VI. PREREQUISITES FOR WORLDWIDE AGROTECHNOLOGY TRANSFER

A. Internationalization of Soil Taxonomy

The key to international agrotechnology transfer is the use of a single soil classification system by all participating countries. Thus, it is a matter of high priority to develop a new soil classification, or to choose one from several existing systems, for use as the standard for international reference and communication. While such action is pending, Soil Taxonomy (Soil Survey Staff, 1975) has emerged as the *de facto* international soil classification system. This

has occurred in spite of the fact that Soil Taxonomy has not been fully tested, especially for soils of the lower latitudes, and is undergoing continuing revision.

In 1979, the Soil Conservation Service of the U.S. Department of Agriculture established an Office of International Soil Classification and Correlation. Functions of the Office are to consider recommendations for revision of Soil Taxonomy from outside the United States, to consult on questions relative to the application of Soil Taxonomy and international soil correlation, to organize workshops for the study of soil classification and soil correlation, and to help organize training in soil survey methods using Soil Taxonomy (Johnson, 1978). This initiative by the Soil Conservation Service is particularly timely as the internationalization of one soil classification system, even on an *ad hoc* basis, is the first essential step for worldwide agrotechnology transfer.

B. Soil Resource Inventories

It is obvious that transfers based on soil classification require knowledge of the kind and distribution of the soils in the recipient area. Historically, soil surveys have been made to acquire and compile this information. Since the subject of soil resource inventories is adequately covered in the proceedings of a workshop held at Cornell University (1977), the discussion in this paper is confined to some general comments.

Land variability may be either systematic or random, but in either case, spatial and temporal variability in land characteristics is a major cause of uncertainty in agricultural productivity and land performance. The objective of soil resource inventories is to stratify both spatial and temporal systematic variabilities so that the corresponding variabilities in productivity and performance can also be stratified. Systematic changes in land, such as climatic fluctuations due to seasons or soil variation related to soil-forming processes, are easily predicted; random variabilities are less predictable, of course, and they include such transient events as weather, a termite mound, an uprooted tree, or an ancient village site. A soil survey should nonetheless alert the users of a site to important random variations in the land that are not delineated on a soil survey map.

It follows from the need for a common international soil classification system that uniform procedures for making and interpreting soil surveys are also needed. Fortunately, relevant guidelines are now becoming available that reflect the experience gained during more than 80 years of soil survey operations in the United States. Much of this knowledge is contained in the Soil Survey Manual (Soil Survey Staff, 1951), which is currently undergoing a complete revision and updating. Laboratory methods and procedures for collecting soil samples have also been standardized (Soil Conservation Service, 1972). Procedural aspects of soil survey including planning, design, staffing, quality control, operations,

cartography, documentation, management, and publication are recorded in the National Soils Handbook, which is now being developed by the Soil Conservation Service (Johnson, 1978).

Soil surveys and classification are not ends in themselves; they are the means to plan for the proper use of land resources. The critical link between a general-purpose soil resource inventory and land-use planning is soil interpretation. Interpretation involves the discovery and recording of the cause-and-effect relationships between observed or measured land characteristics and land performance. Properly developed, soil interpretation can become the means to derive land evaluation for a specific purpose from a general-purpose soil survey. Unfortunately, soil interpretation on an international scale today remains an art. It needs to be made a science.

C. Land Evaluation

In the transfer of agrotechnology, particularly vertical transfers, there are many aspects of soils that are not reflected in their taxonomic names. Slope, for example, is not used as a differentia of classification, but is very important to land use. It is therefore essential to consider soils within the wider concept of land. Land, as defined by FAO, is

> an area of the earth's surface, the characteristics of which embrace all reasonably stable, or predictably cyclic, attributes of the biosphere . . . and the results of past and present human activity to the extent that these attributes exert a significant influence on present and future uses of the land by man (FAO, 1976).

Land evaluation is the process of assessment of land performance when used for specific purposes. A framework for a comprehensive land-evaluation system designed to appraise the suitability of land for crop production has been developed by FAO (1976). This system attempts to relate physical qualities or attributes of land to the environmental requirements of crops for specified levels of management. Examples of land qualities cited in the FAO publication are energy supply (solar radiation, day length, temperature), water supply (precipitation, rainfall distribution, soil-water storage capacity), nutrient supply (soil fertility), oxygen supply in the root zone (drainage), trafficability, erodibility, salinity, foothold, and other qualities.

The kinds of crop requirements that must be matched by the land are photoperiodicity, shade tolerance, soil and air temperature, humidity, wind speed, water needs, mineral nutrition, foothold, soil aeration, tolerance to aluminum and manganese toxicities and trace-element deficiencies, and susceptibility to insects, weeds, and diseases. The Benchmark Soils Project (1979), for example, has found that the soil family of Soil Taxonomy, among other things, stratifies land according to incidence of insects, weeds, and plant diseases. This feature of Soil Taxonomy, which enables it to stratify land into agroecological zones,

provides the link between the scientific and technical grouping of soils. The technical information accessory to the differentiating criteria must be extracted from Soil Taxonomy and reconstructed in a land-evaluation scheme.

Matching land characteristics to crop requirements in land evaluation requires that crops are also stratified in a similar scheme. The latter is attempted by Duke (1978) who is categorizing plants according to their environmental requirements. Such efforts significantly contribute toward achieving the goal of land classification, which is to eliminate trial and error by stratifying the soil-plant-atmosphere continuum into tight crop-performance classes.

Land evaluation is a practical product of soil resource inventories. Its primary use is in land-use planning to guide decisions on land use in such a way that the resources of the environment are put to the most beneficial use for man while at the same time conserving those resources for the future (FAO, 1976).

D. Assembling Crop Performance Data

Up to this point, we have assumed that the relationships between land characteristics, crop requirements, and crop performance are known. In fact, we have simply assumed that crop performance depends on the goodness of fit between crop requirement and land characteristics. Since perfect fit is rarely attained, the effort expended to rectify the mismatch between land characteristics and crop requirement constitutes the management level. The ultimate goal of land inventories is to provide planners with reasonably accurate estimates of crop performance under prescribed levels of inputs.

It turns out, however, that the information required to proceed with the matching process to predict crop performance is not available, or has not been collected and assembled with the matching process in mind. This is largely due to the fact that performance data do not depend only on average, long-term systematic variations in land characteristics but on random weather conditions during critical periods in the crop's life cycle as well. Good performance data are those for which the cause-and-effect relationships between environmental conditions and crop performance are quantitatively known. The time has come to design field experiments to generate such data.

There are two potential sources of performance data which meet the requirements for use in the matching process. These are the International and National Agricultural Research Centers. The value of research data generated in the National and International Centers would be increased if crop performance could be related to land characteristics, crop requirements, management inputs, weather, and any other factor significantly affecting yield. To do this, some international coordination will be required, and recommendations supporting this concept were made in a workshop on "Operational Implications of Agrotechnology Transference Research" sponsored by the International Crops Research Center for

the Semi-Arid Tropics and the Benchmark Soils Project of the Universities of Hawaii and Puerto Rico, held in October 1978 in Hyderabad, India.

E. Information Systems and Data Banks

If international coordination of soil research is achieved so that participating countries make soil resource inventories based on a common soil classification system; and also conduct agronomic experiments on well-characterized and well-monitored sites, it will become profitable to assemble soil and crop performance data in a central place or in a network of standardized data banks. The purpose of assembling such data in readily retrievable form is twofold. First, the crop performance data and the inputs used to achieve that level of performance can be transferred to other similar sites located elsewhere in the world. Second, the assembled information can serve as the basis for soil interpretation and matching crop requirements to land characteristics. For example, the absence or low incidence of downy mildew on maize grown on the thixotropic, isothermic family of Hydric Dystrandepts is not unique to this soil family but to all soil families with isothermic or cooler temperature regimes. Similarly, the high P-fixing capacity noted in this family extends to all thixotropic soil families. Thus, it is not necessary to do research on every site or even on every soil family. Much of the cause-and-effect relations between crop performance and land characteristics can be derived from research on a limited number of carefully selected benchmark soils.

Orderly manipulation of the large number of soil and crop performance data along with weather and management data can only be achieved by means of computerized data banks. The key to the success of such data banks is storage of high-quality soil and crop performance data, collected in a standard way and designed for economy of effort, ease of interpretation, and transferability of information.

It follows that standard soil, climate, crop performance, and management data assembled in a network of data banks should also be coded for storage and retrieval in a standard way. Some uniformity in choice of computer language is also desirable.

VII. CONCLUSION: IMPLICATION FOR AGRICULTURAL DEVELOPMENT

In the next 20 to 25 years, the world will have two billion more people to feed. There is little doubt that the world has the land and the technology to produce

enough food to meet the anticipated population increase. There is, however, considerable doubt as to whether the food will be produced where it is most needed or distributed in an equitable manner.

For humanitarian, as well as for the more pressing reason to secure world order, self-reliance on national food production will continue to be a major international goal. But even the most optimistic forecasts indicate that the emerging nations of the tropics will not be able to avert food shortages. To prevent this, the developing nations and the international development agencies will need to increase research efficiency significantly in the area of food production.

The basic structure for achieving research efficiency already exists in the form of a network of National and International Agricultural Research Centers (NARCs and IARCs). These two types of centers play somewhat different roles. The IARCs conduct research that is more amenable to horizontal technology transfer. For some years now, the IARCs have been developing transferable germplasm and farming systems for the major agroecological zones. It is almost certain that their efforts have lessened the severity of food shortages in the resource-poor regions of the world.

Research conducted by the NARCs has a narrower horizontal scope and is heavily oriented toward vertical technology transfer—that is, rendering scientifically and technically sound technology appropriate for assimilation in local farming systems.

Greater research efficiency in the research centers can be achieved by refining procedures to match and tailor agrotechnology for specific agroenvironments and socioeconomic situations. These procedures, if based on sound taxonomic principles, are the means to organize knowledge so that the behavior and performance of the object being classified and studied may be transferred to other locations where similar conditions exist.

Agrotechnology transfer as a means to meet the world's food requirement and demand will require international coordination. The role of the coordinating body created to perform this task should be to enable countries with probable food shortages to exploit fully the agricultural capacity in a timely manner. To achieve this goal, this body must ensure that (1) a common soil classification system is used by all participating countries, (2) a uniform procedure for making and interpreting soil surveys based on a common soil classification system is employed, (3) standard procedures for matching crop requirements to land characteristics are developed and used, (4) international soil correlation and quality control are maintained in soil surveys and land evaluation, and (5) a tightly knit network of data banks for storing, analyzing, and displaying soil and crop performance data is established. The result will be greater research efficiency and greater economy of action and will contribute to the expeditious agricultural development in regions of the world where it is most needed.

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