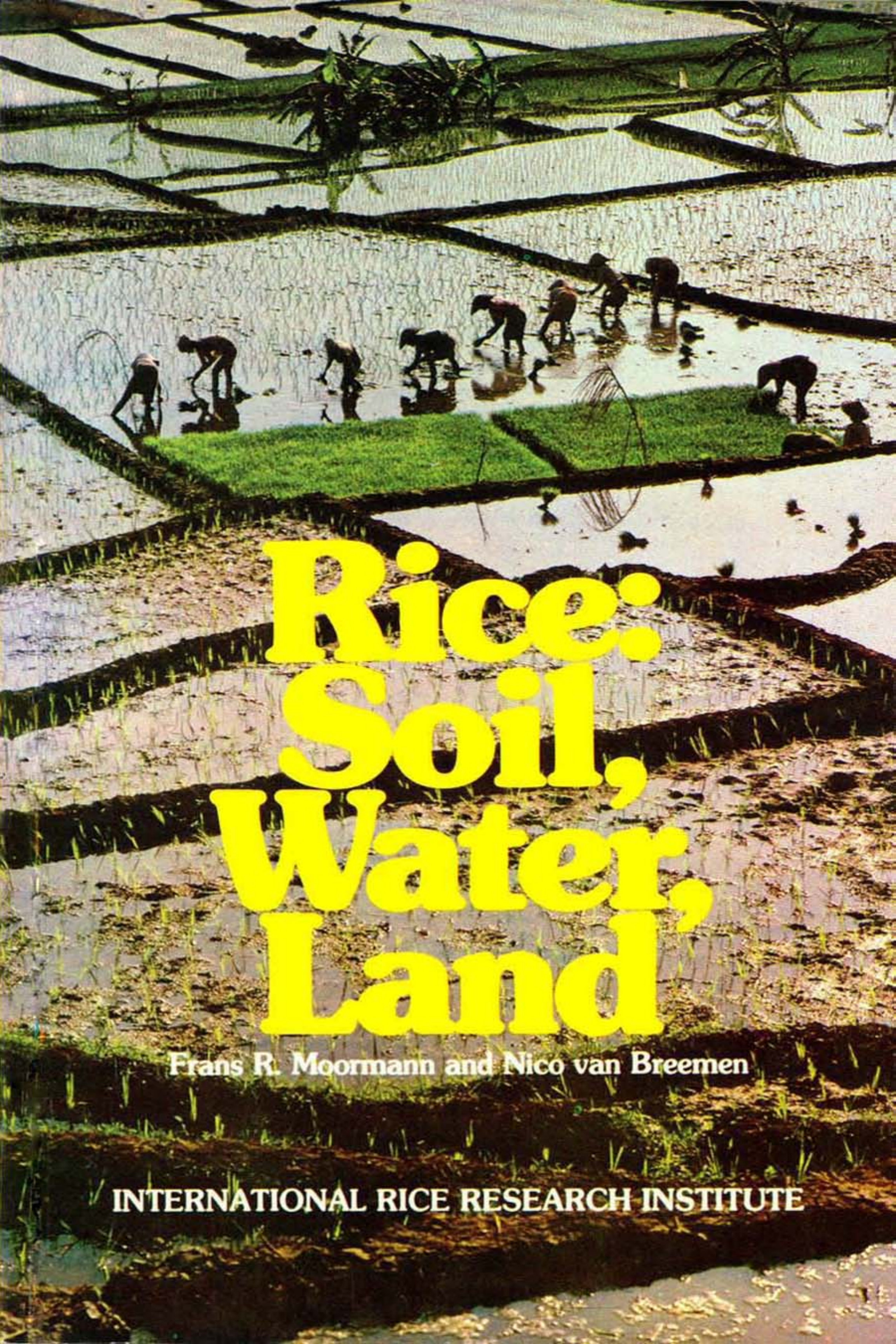

Rice: Soil, Water, Land

Frans R. Moormann and Nico van Breemen

INTERNATIONAL RICE RESEARCH INSTITUTE

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Contents

Foreword

DURING THE PAST two decades sophisticated and specialized research on rice and its requirements for increased production has expanded greatly. Little of this research, however, focused on the diversity of environments in which rice is grown. Differences among soils, for example, have often been overlooked or ignored. Such neglect is inconsistent with increasing efforts to devote research to the needs of rice farmers and the locale-specific problems they face.

The authors of this book strongly emphasize *the need to study interrelationships between performance of the rice crop and its natural or man-modified environment.* They have taken a major step toward filling the knowledge void on soils and rice. Further, they have stimulated others to do research in this field. Thus, they perform a service both to soil scientists and agronomists for whom the book is primarily intended, and to other production-oriented scientists and educators whose accomplishments depend upon a knowledge of soils.

Dr. F. R. Moormann as senior author drew on more than 20 years of research and field experience with rice soils of South and Southeast Asia and of West and Central Africa. He worked on this book at the International Rice Research Institute (IRRI), while on a one-year sabbatical leave from the International Institute of Tropical Agriculture (IITA). While at IRRI, Dr. Moormann undertook collaborative work with IRRI soil scientists and with Dr. van Breemen who was assigned for study at IRRI by the Netherlands Government. Dr. van Breemen has worked with rice soils in South and Southeast Asia, and in South America. Hence, while the authors refer to the works of others, they have had direct experience with the total subject area the book encompasses.

This book represents a growing commitment on the part of IRRI, IITA, and other international and national agricultural research centers to an improved characterization of the field environment for rice. Its publication should encourage greater research in this area.

N.C. Brady, Director General
International Rice Research Institute

13 February 1978

CHAPTER 1

Rice and its environment

KING PARAKRAMA THE GREAT, who reigned in Sri Lanka during the 12th century, said,

> "In my kingdom are many paddy fields cultivated by means of rainwater, some cultivated by means, of perennial streams, and some by means of tanks both small and big. By rocks and by many thick forest is the land covered. In such a country, not even a single drop of water obtained from rain, should be permitted to flow to the ocean without having given its full benefit toman".

We, who live some 900 years later in a world of ever increasing development of science and technology, must acknowledge the King's foresight and wisdom. Indeed, placing Parakrama Bahu's command within the context of Sri Lanka's environment and climate, it is clear that at that time there was a profound understanding of crop ecology and of important factors guiding agricultural production.

Certainly, it may be assumed that the environmental requirements of rice, the main staple crop in Asia then and now, was considered prominently in the statement. The vagarious rainfall in Sri Lanka, which served as a sole water source for rice production, must have been observed and understood. And equally certain, both the farmers and the King must have had a great deal of practical knowledge of the soils the water was to serve, and of those portions of the landscape for which control of a basic source, the rain, would have a maximum beneficial effect.

If you fly over the drier, northern part of Sri Lanka, the lush rice-growing valleys, served by water from a multitude of small and large water reservoirs, and the extensive system of irrigation canals connecting those reservoirs, can be observed as proof of an ingenious adaptation of the rice crop to the environment.

Nor is Sri Lanka an exception. Records from a much earlier stage of the recorded history in Asia point clearly to the fact that from an early stage in the domestication of the rice crop, Asian farmers have relied heavily on their knowledge of soils, water, and land to produce rice and guarantee their livelihood.

This, then, is the leading theme of this book. We try in a modest — and surely very incomplete — way to consider and discuss the multitude of environments in which rice is, or can be, grown.

Modern agricultural science has increased rice yields to levels that would have been unbelievable as little as 30 years ago. Manipulation of genetic resources has created rice varieties with a yield potential several times that of the old traditional rices. Control of water, now almost completely effective in the countries of East Asia — China, Japan, and Korea — has increased yields and crop security, and has been a main factor in the extension of highly productive rice cultivation to areas where rice is a relative newcomer.

Introduction of modern land and plant management techniques, such as mechanization, the use of chemical fertilizers, and chemical pest control, has borne its share in the success of this modern rice technology, which started many years ago in the more developed countries and which is progressing, slowly but steadily, toward the less favored rice-growing nations, located mainly in the intertropical zone. Yet with all the sophisticated and increasingly specialized research on rice and its requirements for optimum production, the diversity of the environments in which the farmer produces his crop has received much less attention than it merits. The modern, highly productive rice varieties are not, and cannot be made, universally adaptable. Management techniques may lead to increased production in one environment, but may have less, or negative, results in another.

Such locale-specificity of measures to improve rice production is valid for almost every endeavor to produce a better rice crop, even if the tremendous variations in the socioeconomic environments are not considered. To paraphrase a statement of the French scientist-author Pascal: what is the truth on this side of the Pyrenees, may be falsehood on the other side.

This book does not attempt to review all that is known on the relationships between the rice crop and its environment. That could not be done in view of the tremendous volume of information available on the various aspects of the subject. For instance, the biological aspects pertaining to specific varietal characteristics and physiology will hardly be touched upon, important as they are. Transient characteristics of rice-growing soils, more specifically the fertility of the surface soil as determined by fertilizers, either are not or are only summarily treated, as is the subject of soil testing by chemical and physical laboratory analyses. Even in its designated area, the book cannot be complete because there is too great a diversity of environments to allow description and analysis to any degree approaching completeness. What we try to do is to emphasize the importance of various aspects of environments for rice as a food crop.

In Chapter 2, we give attention to the physiography and geomorphology of major rice-growing regions, and to the components of the landscape, or landforms, that are particularly suited for rice growing. The understanding of the physical landscape is of considerable importance, and is a subject too often neglected. Both the potential and the possible problems of a given rice field are closely related to the position of that field in the overall landscape. The dynamics of many soil problems such as salinity, nutrient deficiencies, and

Throughout this book the authors emphasize the importance of environment – soil, water, land – to rice at a food crop. The progosed terminology should help to improve communication among workers dealing with the world's rice-growing soils, whether on farms at 1,300 m elevation as seen here in Bhutan's Wandi Phrodang Valley, or on farms in the more common lowland paddies of Southeast Asia.

iron toxicity cannot be satisfactorily studied without relating them to a specific landscape position. The wide diversity of such positions in rice-growing lands is illustrated even though the subject is not treated extensively.

A major factor in rice growing is water. Water is probably more important for rice than for almost any other cultivated plant in view of rice's *amphibious* or semiaquatic nature. Water, which we deal with in Chapter 3, is the key to successful rice growing, and will be the key to the successful extension of rice growing to new areas. Also in Chapter 3, we give attention to the fact that the existing typology of rice-growing lands is highly confusing and often misleading. The simple term *upland rice* has a great number of connotations and definitions, depending on the area, the country, or the region in which the crop is grown, and all too often depending on the whim of the user.

Water being as fundamental to rice growth as it is, we have tried to analyze various kinds of rice lands in terms of their landscape position, their natural supply of water from the different sources, and man's action leading to modifications of the natural water regime. We believe that the typology and nomenclature we propose may, if properly used, help diminish the misunderstandings regularly created by the use of the existing, confusing terminology.

The subject matter of Chapter 4 is classification of soils on which rice is grown. This is probably the most soil-oriented chapter, and we consider it to be most important for communication between scientists dealing with rice and soils simultaneously. A quick review of publications dealing, for instance, with fertilizer experiments on rice will reveal mostly nothing more than that the soils in question are sandy soils, clayey soils, wet soils, or red or black soils. The reader is at a loss as to what kind of soil is meant or, even more serious, as to what other soils the reported results are applicable.

While writing about classification of rice-growing soils, and actually trying to classify such soils based on data from personal experience and from the literature, we had to make a decision on which soil classification system to use. Our choice was the U.S. Department of Agriculture's *Soil taxonomy* (USDA, 1975) which had been developed since the early 1950's by the concerted efforts of pedologists from the U.S. and also from many other countries. Among the advantages of using *Soil taxonomy* is that it provides a universal system and is open-ended, leaving the possibility for improvement and for the introduction of new units or taxa as knowledge of soils, especially those in the tropics, increases. Other universal systems lack the flexibility and precision that *Soil taxonomy* provides. We have given, where possible, the equivalent mapping units used in the legend of the *FAO/Unesco soil map of the world* (1974).

The taxonomic approach to soil classification is rapidly gaining ground in many of the world's rice-growing countries, and that alone would be adequate justification for Chapter 4, whose main purpose is to improve communication between scientists and others dealing directly or indirectly with rice-growing soils.

Most rice is grown where the soil is submerged during part or all of the growing cycle, and where management techniques are oriented toward increasing and regulating the period of submergence. In many instances submergence has become so dominant that rice soils are equated with soils found under the submerged conditions of rice fields. While on semantic and technical grounds we do not agree with use of the term *rice soils* in scientific publications, in Chapter 5 we give ample attention to the extremely important effects of the aquatic water regime on soil properties and to the changes, both temporary and enduring, which occur in soils subjected to such a regime. In Chapter 5, moreover, an effort is made to incorporate certain major, measurable changes in the taxonomic classification discussed in the previous chapter.

In Chapter 6, we discuss certain parameters pertaining to soils, water, and other characteristics of the environment as they relate to the growth and performance of the rice crop. In most cases, we emphasize the *problem* aspect of these parameters. To fit them into the overall approach of this book, information is given on dynamics and variability in time and space of such characteristics as soil salinity and the interflow phenomena.

The last chapter — probably the one that will leave you with the most questions unanswered — tries to *transpose* much of what we have written in terms of practical evaluation of the qualities of a given field for growing an economically remunerative rice crop. In the research for Chapter 7 it became increasingly clear that little is known, at least in a quantitative sense, about the optimum conditions — and the permissible constraints — that rice, or any other crop, requires. Certainly, we can qualify certain conditions of the land as too dry, too acid, or too poor for rice, but the answer to the logical questions of how dry is too dry, or how poor is too poor, is more difficult to give. Hence, in Chapter 7, we can only indicate relationships between the performance of rice cultivars and the properties of the environments, which are defined as land qualities in modern land-evaluation parlance.

The study of the interrelationships between crop performance and the natural or man-modified environment is a new and exciting one. We hope this book may, if only on a modest scale, contribute to the furtherance of such research.

CHAPTER 2

The geography of rice (Oryza sativa L.)

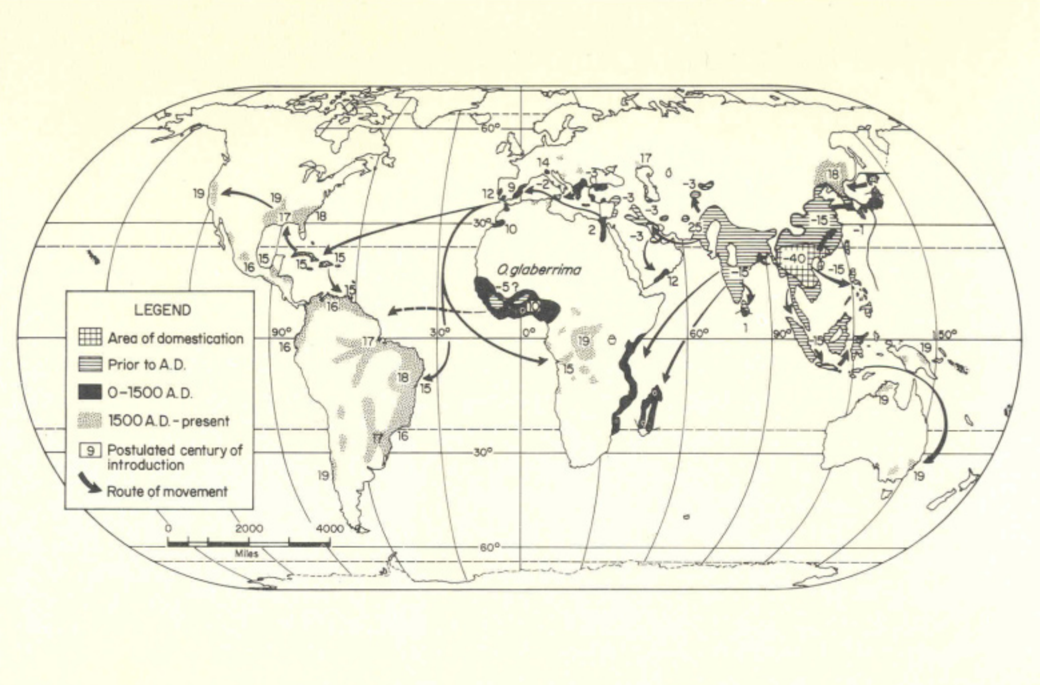
ORIGIN AND DIFFUSION OF CULTIVATED RICE

Two species of domesticated cultivated rice evolved from a pool of wild *Oryza* species (see Chang, 1976). *Oryza glaberrima* (Steud), which we do not peruse herein, is found in West Africa's middle Niger valley and in a few secondary centers. That species mostly grows wild as a deep-water rice in seasonally flooded portions of West African river valleys. The same pattern is seen in Brazil's Amazon basin. Only locally is *O. glaberrima* managed as a dryland crop in the high rainfall zone of West Africa. More frequently, it is considered a weed in recently developed fields of *O. sativa.*

Oryza sativa was domesticated in tropical and subtropical Asia but the center of domestication is a matter of contention. One school assumes its simultaneous domestication in various centers extending from the plains below the eastern foothills of the Himalayas, through upper Burma, northern Thailand, Laos, and northern Vietnam to southwest and west China (Chang, 1976). Another school postulates a more limited center of origin, notably the inland valleys in northern Thailand, the Shan states of Burma, and the adjacent area of Laos (Huke, 1976). The dependable monsoonal rains of that area, its warm and humid environment, and the specific physiography of the valleys with their multitude of wet and seasonally shallowly flooded grassland depressions offered an ideal environment for *O. sativa's* domestication.

From its initial point or points of cultivation, *O. sativa* has spread over a considerable part of the earth and has become the major food crop for a large part of the world population. The historical diffusion of rice is represented in Figure 1.

Varietal adaptation — including the development of the main subspecies indica and japonica — and the improvement of land and water management practices, which changed and optimized rice's edaphic and climatic environment, have pushed rice growing well beyond the conditions of its point of origin. Rice now grows as far north as latitude 53°N in the Amur River valley on the China-Russia boundary, requiring varieties with a far different photoperiodicity and temperature tolerance than those that grow close to the equator. Rice's requirements for water have, in the process of diffusion, been met by selection of areas with sufficient rainfall, by extension of the culture in



1. The historical diffusion of *Oryza sativa* (Huke, 1976).

wet lowlands, by water conservation, and ultimately by irrigation. Thus, the limits of rice's diffusion throughout the world are imposed mainly by the temperature regime, while within that large *zone,* the availability of an ample water supply has always been a determinant of the distribution in the landscape of rice as a food crop.

RICE IN THE LANDSCAPE

Rice, through varietal adaptation, can be grown as a dryland crop in the more humid areas, but it is — by origin and by preference of most cultivators — mainly a wetland crop. Agricultural systems based on rice as the food staple are thus clearly lowland systems. That fact is seen in Figure 2, which estimates the distribution of the world's rice crop. Note that the major areas are the extensive lowlands in southern and eastern Asia, areas almost exclusively river basins and deltas with their contiguous coastal plains.

The distribution of rice in the landscape is best understood through knowledge of the semiaquatic or amphibian nature of the rice plant. Rice is not an aquatic plant in the botanical sense, as proven by its root system, but it thrives in waterlogged soils where no other grain crop survives. Only certain aroids and sago palms *(Metroxylon* sp.) can compete with rice as a food crop adapted to wetland conditions, but they are of minor importance.

The semiaquatic character of rice was the key to the development of wet lowlands in Asia at an early stage in the history of agriculture. Rice grew in those lowlands without extensive drainage and flood protection works, such as those required to develop wetland areas for nonaquatic upland crops. There are, of course, areas where neither rice as a colonizing crop, nor the necessary techniques for flood protection and drainage to grow upland crops were available. Such wet lowlands, mainly in tropical Africa and South America, remain largely underutilized. A typical example is the coastal delta of the Niger River and its adjacent lowlands, where an estimated 400,000 ha of potentially valuable lowland is virtually unused for agriculture. Nonutilized lowlands in the basins of major South American rivers form an even greater reserve of potential wet rice lands.

In the presumed heartland of rice growing, the highlands of central Southeast Asia, the general relief is rugged and determined by series of more or less parallel ridges, separated by flat-bottomed valleys (Fig. 3). Agriculture is mainly concentrated in those valleys, a considerable portion of which have wetland or hydromorphic soils, In sharp contrast, the steep slopes of the ridges bordering the valleys remained under forest. Only recently have the valley farmers—due to population pressure—encroached on the steep land, but no sedentary agriculture has developed. In many places, the encroachment on the valley slopes has accelerated erosion and led to rapid land deterioration. On the crests of the ridges, and on the small, high plateaus, the staple food crop is mainly rice in a shifting-cultivation system on well-drained soils.

The relatively low importance of the rice grown in shifting cultivation is illustrated in northern Thailand, where the lowland population exceeds the hill-tribe population by a factor of 50, but where the total surface of the lowlands is less than 15% of the total land surface. Clearly, an agriculture based mainly on the use of well-defined and confined lowlands, where rice grows in wet soil, is a natural adaptation of cropping patterns to land conditions in an area.

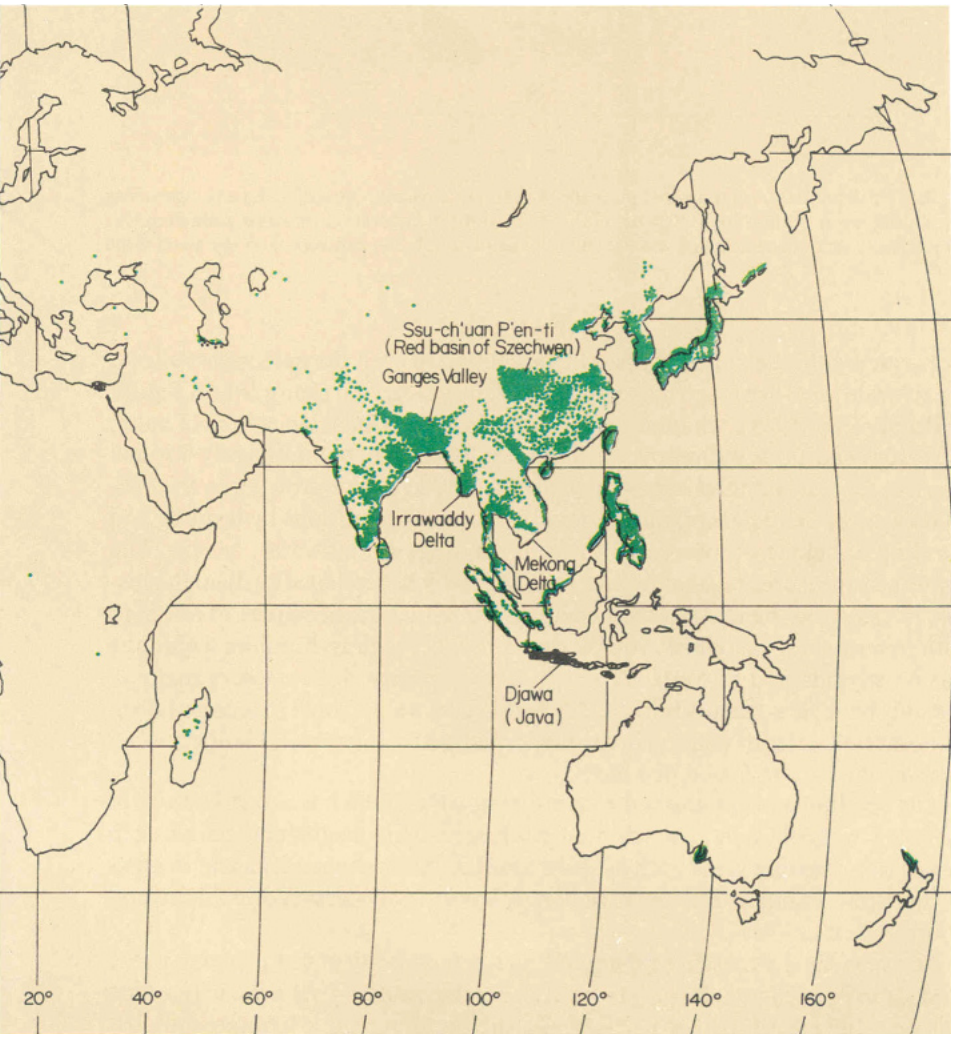
Below the hilly heartland of *O. sativa* rice growing extended to the major river valleys, deltas, and coastal plains. Physiographically, the land area to the south and east of the Himalayas-Tibet highlands and its eastern continuation is characterized by broad lowland plains. These include the plains of Yangtze, Mekong, and Brahmaputra-Ganges river systems, the sources of which are in the Himalayas-Tibet highlands. There are also the shorter river systems of the Red River, the Chao Phraya, and the Irrawaddy, which start from the hill areas southeast of the Himalayas. All these rivers have extensive middle and lower valleys as well as wide deltas. It is here that, over the centuries, the major extension of rice cultivation took place mostly on lands that because of their hydromorphic nature were exclusively suited for rice as the major food crop.

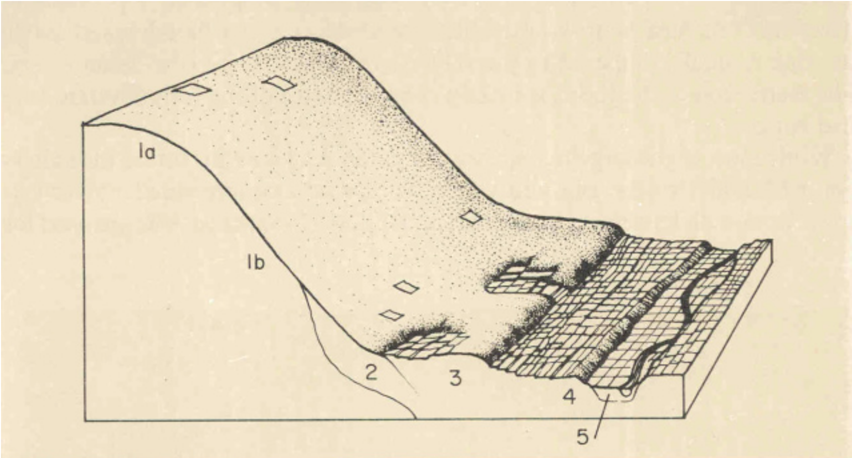
From a global point of view, there is no other area in the rice-growing zone — as it is limited by temperature restraints — with major river valleys and deltas comparable with those east and south of the Himalayas. The deltas and adjacent river plains of the major African rivers are much smaller. The two major equatorial rivers, the Congo and the Amazon, have small deltas, although large zones of wet lowlands exist in their middle course. The Indus

2. The worldwide distribution of rice cultivation.

River valley in Asia is an exception inasmuch as its total surface devoted to rice growing is small compared to the valleys and deltas of the east Asian rivers. The restriction of the Indus is mainly climatic. Most of the Indus system is in arid zones.

While most of the large rice-growing areas in Asia are thus found in association with major rivers, rice cultivation has spread also into smaller river valleys. Almost all depression landforms in South and Southeast Asia are used for





3. Rice cultivation in a ridge-valley landscape of northern Thailand (no scale): shifting cultivation on undulating to rolling high plateaus (la), recent shifting cultivation on slope colluvium (2), paddy lands on river terraces (3 and 4), and alluvial plain 5). No cultivation on the steep slope (1b).

rice growing, to the point that paddies are found in even the narrowest valleys. Small-scale land-use maps make this abundantly clear. An example is in Figure 4 (Panabokke, 1978), which shows the distribution of such lands in Sri Lanka.

Water conditions within the lowlands are, of course, not uniformly optimal for rice. Of fundamental importance for the spread of rice growing in the lowlands was the artificial creation of aquatic (flooded) conditions by leveling and bunding of fields to conserve water from flooding, groundwater, or rain. The combined measures of leveling and bunding, which developed early in the history of rice growing in Asia, tremendously increased the hectarage of rice land with potential for sustained crop production. The leveling-bunding technique was mostly adapted to wetlands and to lower concave slopes, where many of the soils have slow permeability and where excess water from streams and from adjacent higher lands collects in the higher bunded rice lands and is distributed by overflow to the lower rice lands.

The leveling and bunding of rice-growing lands, which is second nature to the rice farmers of Asia, was adopted as a basic land management technique in newer rice-growing areas such as those around the Mediterranean and in parts of the United States. The practice is not, however, widespread in Africa and South America.

The next logical measure for extending the possibility of rice growing in the landscape is, of course, irrigation from an outside source. Irrigation of rice land was possibly established as early as was the bunding and leveling technique, and again resulted by and large in the extension and improvement of the aquatic environment optimal for rice.

4. Distribution of rice areas and rainfall zones in Sri Lanka (adapted from Panabokke, 1978).

Pluvial rice land in shifting cultivation in northern Luzon, Philippines.

With irrigation, rice will grow in many arid zones where the natural water supply is insufficient. Moreover, with irrigation, rice can be grown on existing rice lands in the dry season. Hence, irrigation leads to an expansion of the rice hectarage, both in space and in time.

Wetland rice growing also expanded from its *natural* lowland position to higher lands, and even to steep slopes, provided that a source of irrigation water was harnessed at a yet higher elevation. Thus, the use of sloping uplands for terraced paddies is clearly related to the presence of such water resources in the higher aspects of the landscape. To a certain extent, the extension of wetland rice up the slopes can be found anywhere in Asia where irrigation water can be made available. But the major impact of irrigation has been in the lowlands of the rice-growing zones of the world, both in the small valleys and on the major plains and deltas.

While most rice is aquatic, an estimated one-sixth of the total rice land is reported as upland (De Datta, 1975), i.e. land where rice grows in fields not bunded or leveled and that depends exclusively on rainfall for moisture. This estimate may be exaggerated, because in the newer rice-growing areas such as

West Africa, most of the so-called upland rice-growing areas are in reality lowlands with temporary high groundwater (hydromorphic soils). The main difference between African and Asian rice lands is that Asian techniques for water retention by leveling and bunding are not applied in Africa. If only the rainfed rice grown on well-drained land is included under the term upland, such land may not be more than 10% of the total rice land.

The occurrence of rice as a crop in freely drained uplands is restricted to zones with a sufficient water supply from rain. Thus, semiarid or drier zones are excluded from this type of rice cultivation. Within the climatic restrictions. however, rice is grown on a wide range of landscapes and topographic positions. Slopes may surpass 100% in shifting cultivation systems, under which most of the rice is grown in freely drained uplands. However, such steep, cultivated slopes form only a small portion of the dryland rice land. A much larger proportion is found on moderately to gently sloping plateaus and peneplains as, for instance, the volcanic plateaus in Vietnam and the Philippines (Batangas area of Luzon), and the extensive savanna *(cerrado)* regions of central Brazil.

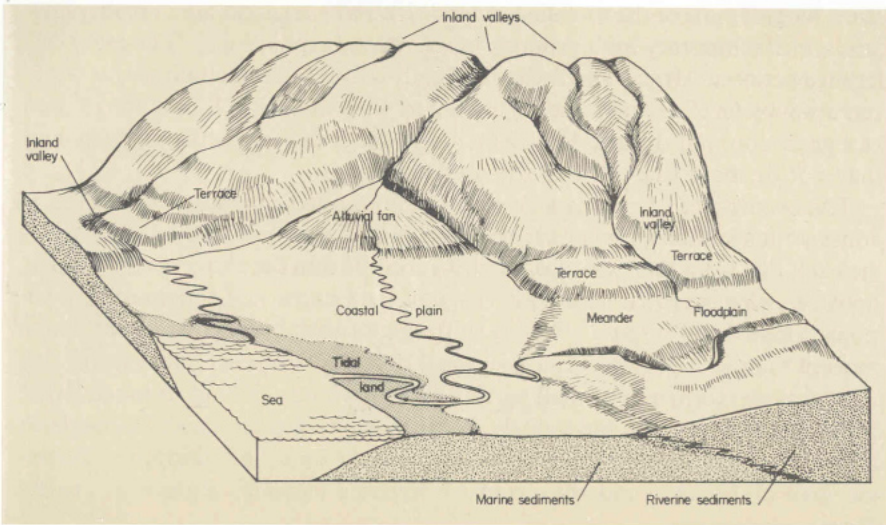
Intensified cultivation of rice in freely drained uplands, without or with only short periods of fallow, is restricted to much flatter terrains and to lands that are not too severely subjected to erosion. Therefore, while dryland rice land can be found in most aspects of the landscape, it is restricted mostly to lands that are gently sloping.

MAJOR LANDFORMS OF LOWLAND RICE-GROWING AREAS

The geomorphology of the major and minor lowland rice-growing areas is diverse and their surface relief varies from place to place. Within this book it is impossible for us to describe even the larger rice-growing lowland areas — those connected with major river systems — in any detail.

Regional studies of the physiography and soils of major and minor agricultural development areas have, in the last decade, shed much light on geomorphology and landforms in the lowlands of the rice-growing zones. For a major proportion of such lands, more or less detailed geomorphological studies, frequently made in conjunction with soils and hydrologic studies, are now available. Examples are the studies by Brammer (1971a,b) of the plains in the Ganges-Brahmaputra river system in Bangladesh; by Van der Kevie and Yenmanas (1972) and Takaya (1971) in the Chao Phraya basin of Thailand; by Moormann (1961) covering several parts of the lower Mekong basin; by Brinkman and Pons (1968) for the coastal plains of the Guianas in S. America, and by ILACO-NEDECO (1966) for the lower Niger River delta in Nigeria. This list could be easily increased, and could include detailed descriptions of the smaller rice-growing lowland areas.

Within the wide diversity of geomorphological patterns found in rice-



5. Schematic representation of the major landforms used for rice growing.

growing lowlands, certain elementary landforms repeat themselves. Major landforms discussed herein are schematically represented in Figure 5.

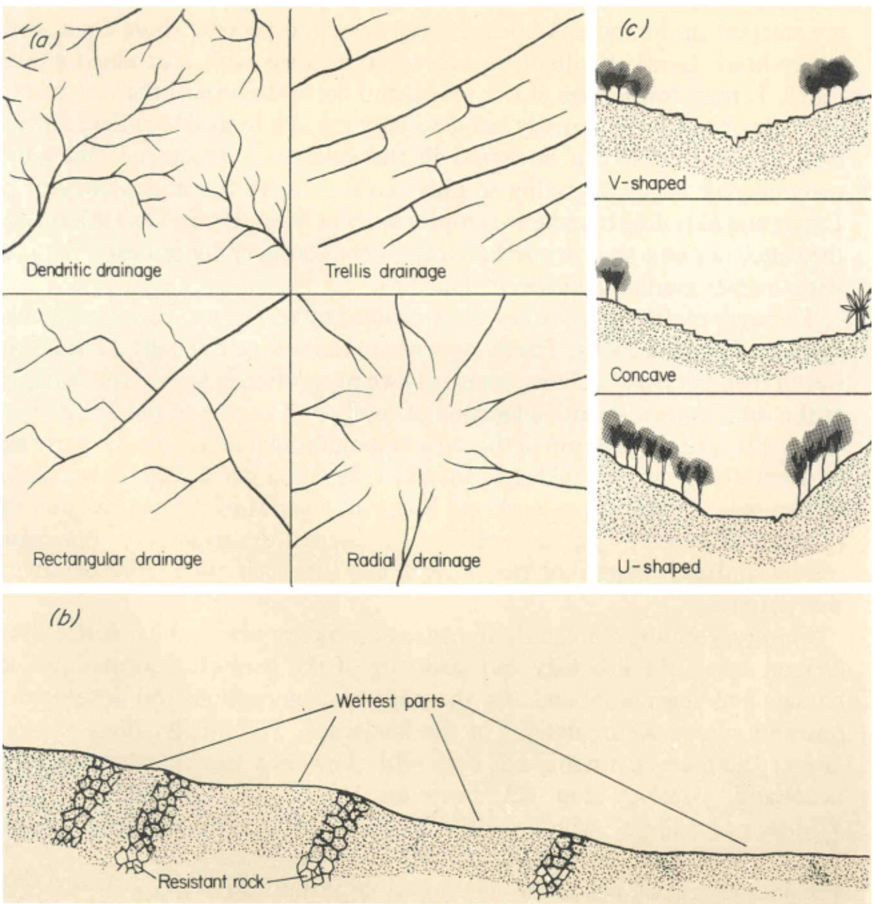
Inland valleys

A considerable proportion of wetland rice is grown in valleys of modest to very small size. A precise definition is difficult, but in the present context inland valleys are the lowlands of the upper reaches of major and minor watersheds, where the sediments — either alluvial or colluvial — are derived from the adjacent uplands. Soils, therefore, frequently reflect one or more characteristics of the adjacent dryland soils, even though certain properties such as base saturation and clay mineralogy may have altered considerably under the specific hydromorphic regime of the valleys.

In many areas, inland valleys form the major resource — if not the only one — for wetland rice growing. A typical example is seen in Sri Lanka, where the larger part of wetland rice growing is confined to inland valleys (Fig. 4). Physiographic conditions similar to Sri Lanka's dominate in many of the rice-growing areas of West Africa, and much of the ongoing development of rice growing is found in inland valleys. The list of such examples could be long because in all major and minor river basins, inland valleys are preferred sites for rice growing, especially in most of Asia.

Inland valleys vary widely in a number of characteristics influenced, among others, by inequalities of slope, rock resistance, structure, and geologic-geomorphologic history of a region. The physiographic variations of inland valleys cannot be detailed here, but a few are cited because many of the soil and hydrological characteristics of rice lands in such valleys are directly related to the specific geomorphology of the landscape. Inland valleys conform to the drainage pattern of the physiographic region in which they occur. Some of the more important drainage patterns are diagramed in Figure 6a.

- *Dendritic:* a nonsystematic or treelike branching pattern of valleys extending in many directions. This pattern is formed on rocks of uniform resistance, often in peneplains of horizontal sedimentary units and complex metamorphics without a dominant slope or structural control.
- *Trellis:* a branching pattern controlled by the presence of folded and faulted strata. The major primary and secondary valleys are parallel to the rock strata and are connected by short and often steep and narrow cross valleys.
- *Rectangular:* a pattern where the branching is controlled by the presence of



6. Drainage patterns of inland valleys (no scale): (a), longitudinal cross section of a stepped valley (b), and transversal sections of the main valley types in use for rice (c).

approximately right-angle faults or joints. This pattern is often found in areas of old methamorphized crystalline rocks.

- *Radial:* a pattern of drainage valleys radiating outward from a common higher center or, alternatively, converging in a common circular basin.

Several other drainage patterns can be distinguished but they are of lesser importance in rice lands.

The general relief of the terrain in which rice-growing inland valleys occur influences slope, cross section, and general hydrology of the valleys. Moreover, the general relief is an important factor regarding accessibility to the fields and general cropping patterns of the area. For descriptive and practical purposes, the general relief of the land systems with inland valleys can be described as mountainous, hilly, rolling, or undulating.

Inland valleys vary widely in their longitudinal profile. Generally, gradients are steepest in the mountainous and hilly areas, especially those close to the valley head. Gentle gradients are common in areas with a subdued general relief. Terrace forms, size of rice fields, and the hydrology of the rice lands in the valley bottom are strongly influenced by the longitudinal gradient. A typical example of this can be found in the valleys of structured and joined metamorphic rocks in rolling to hilly terrains, as in the midcountry of Sri Lanka and in rolling basement-complex areas of West Africa. On a microscale, the valley bottoms show a number of steps consisting of flat or nearly flat parts with steeper gradients between (Fig. 6b).

The steps of the *stepped valley* are controlled mostly by structural differences in the underlaying rocks. The flat sections of the steps are usually considerably wetter than the steep sections, especially when, as often happens, the flattening of the relief coincides with a location of confluence of two or sometimes three valleys. In an extreme form of this type of longitudinal relief, the flat parts may be separated by steep and deeply incised valleys too narrow for development of rice fields. There, rice lands are found in a series of discontinuous small plains, connected by narrow, and steeply incised drainageways. The *inland swamp* landscape in parts of Sierra Leone and Liberia is quite representative of this pattern.

The cross section of inland valleys varies to a great extent as a function of the general relief, the lithology and structure of the geological formations, the climate and vegetation, and also the stage of geomorphological development (erosion versus accumulation) of the landscape. Essentially, three types of cross section are distinguished, each with their own specific patterns of rice lands and hydrology (Fig. 6c). These are:

- V-shaped valleys, which form a well-defined central drainageway and where side slope terracing is current.
- Concave valleys, where the transversal slope diminishes gradually from the sides to the center, with almost flat parts and, often, a poorly defined drainageway.
- U-shaped valleys, where the transversal slope is absent in the bottomland,

These inland valleys in Johore, Malaysia, show a dendritic drainage pattern. (Photo by M. Flach, Wageningen)

showing a more or less sharp nick point on the transition to the adjacent higher land (Fig. 7). Frequently, rice land is confined to the bottom of the valley, but terracing of the slopes may occur where conditions are appropriate.

Between these three forms many transitions exist, with the cross section changing from one form to another along a single valley.

Alluvial fans and piedmont plains

The alluvial fans and piedmont plains are found between hilly areas and lowlands where sediment-charged water from the rivers and creeks abruptly loses much of its velocity as it enters the flatter lowland. The classical landform is that of a fan, high near its apex and descending toward the lower plain with which it blends in its lower reaches. Stream channels shift regularly after they locally build up the land, so that several channels may be found in a single fan. Where larger valleys border hill ranges, a series of overlapping fans is formed, resulting in gently sloping areas or piedmont plains.

A well-formed alluvial fan shows a definite gradient in texture and overall soil drainage. The fan's upper part is generally coarser textured, often with gravel beds at the surface or at shallow depth, and is often freely to excessively

7. This rice-growing area near Taunggyi, Burma, typifies the U-shaped valley. Note the terracing of the lower sideslopes on the left of the valley in the background. (FAO photo by I.W. Kelton)

drained. Soils become more clayey and more poorly drained toward the fan's lower, wider part.

There are, of course, variations on the general alluvial fan pattern, depending on the speed of discharge of the water from the hills and the nature of the sediment load as determined by the soils and the surface formations in the watershed area. In the more arid climates, where discharge from the highland is in the form of flash floods, the alluvial fans — and often the piedmont areas — are coarse textured and excessively drained throughout. In such areas little or no rice is grown.

Where sediments are more clayey and flooding is gentler, the whole of an alluvial fan may have a medium texture or finer, especially in areas where clays, or formations which easily weather to clay, are dominant in the watershed area. That is the case for many alluvial fans of volcanic areas, such as in Java, where aquatic rice cultivation has extended from the lower part of the fan to its apex. Generally speaking, however, wetland rice in alluvial fans is found mainly in the lower, more clayey aspects of the landform. Terracing and irrigation are common on this land in Asia.

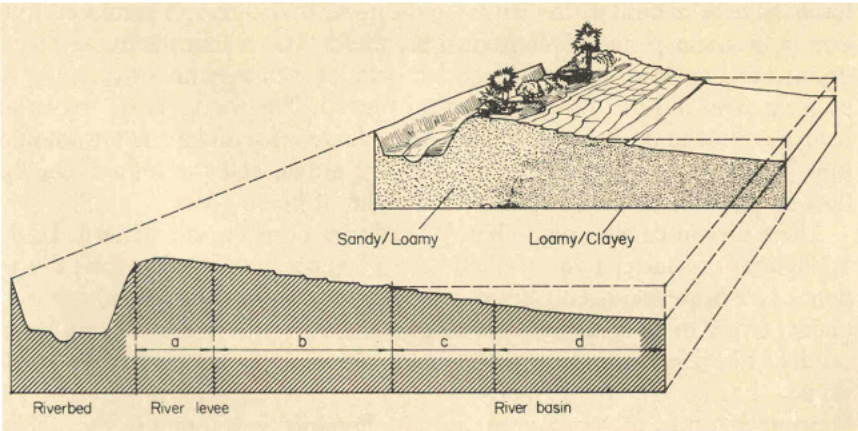
Meander floodplains

Meander floodplains are found mostly in the middle course of rivers. Landforms composing this type of landscape are riverbeds with stream channels, river levees, and river basins (Fig. 8). Sedimentation on the levees results from floods, which have a relatively high velocity close to the channels. Hence, such river levees commonly have a fine sandy or medium texture. Away from the river, where the velocity of the floodwater is less or nil, the finer particles remaining in the floodwater settle, and the soils formed are considerably more clayey. Because of slow sedimentation, the basins are lower and more hydromorphic in nature than the levees. There is thus a distinct gradient away from the river, starting with medium-textured, well-drained soils, going to very fine, clayey, poorly-drained soils, and eventually to transitions to peaty soils in those parts of the basins that never dry.

Numerous variations exist on the basic meander floodplain pattern. The river channel commonly shifts, which cuts away the levee on the outside of the meander bend and deposits levee material on the inside. Often, meanders are abandoned when the river cuts a new bed and the old stream channel remains as an isolated lake, known as an oxbow lake.

Some rivers' floodplains show wide belts of abandoned river beds, accompanied by remnants of higher river levees. Such wider meander belts occur most conspicuously in the river valleys of the semiarid areas, sometimes to the point that virtually the whole floodplain is occupied by the pattern and at most only small basins are found.

Another pattern is found where the river abandons its bed completely, forms a new bed, and builds a new river levee system where previously there was a basin. This lateral shifting of river channels is common in most lower reaches of main rivers, but may also occur upstream where rivers enter a wide intramontane plain The old levees, with a variously silted-in river channel,



8. Relationship between type of cultivation and landscape position in a meander floodplain (vertical scale exaggerated).
a — nonflooded, used for garden and dryland crops.
b — shallow flooding, used for transplanted rice (semidwarf varieties possible).
c — moderately deep flooding, used for transplanted rice (no semidwarf in wet season).
d — deep flooding, used for direct-seeded rice (deep-water varieties).

9. This meandering river in Central Luzon, Philippines, shows the concentration of homes, roads, and trees on the levees, and the rice fields in the basin.

remain visible in the landscape as low ridges, although they may become covered by basin sediments when the whole plain builds up.

The mode of flooding in the river plain depends on several factors, including the overall lengthwise gradient of the plain, the rainfall regime of both the plain and the watershed area, and the degree to which the riverbed and adjacent levees have been built up in relation to the lower basin areas. A common situation in meander plains of monsoonal Southeast Asia is that the highest well-drained and medium-to-coarse textured parts of the levees are used mainly as housing sites and for dryland farming (Fig. 9). The more clayey transition from the levee to the basin is used for transplanted rice under shallow inundation. In the basins deep-water varieties are grown and the lowest, deeply-flooded portions of the basin are the domain of floating rice.

There are, of course, a number of local variations on this pattern. In the floodplains of shorter rivers, which have a steeper gradient, the low, deeply flooded basin areas are generally absent or greatly reduced in size. In such river plains, either there is no deep flooding or it occurs only briefly during heavy rainfall. The deep-water and floating rice components are absent in such conditions.

Another source of variation in meander floodplains is found in the texture gradient from the levees to the basin. In all cases, the basin sediments form finer soils, but fine clay is not necessarily always found in the basin. The Tista floodplain in Bangladesh, for example, has silty basin soils. Nevertheless, most basin soils have a clayey texture, even in the small river plains.

The transition between meander floodplains and the coastal plains is generally gradual and a boundary between the riverine and marine parts of major and minor deltas is therefore difficult to draw with any precision. Moreover, older marine-deposited areas may become covered by younger meander floodplains. In at least two major river deltas of Southeast Asia (Chao Phraya, Mekong), this vague transitional area is characterized by the presence of sediments deposited in a brackish water environment. The resulting formations are characterized by the presence of acid sulfate soils.

Lacustrine floodplains

Lacustrine floodplains occur in several landscape positions and may form part of major river valleys. An example of a well-developed lacustrine floodplain, used for wetland rice growing is the plain surrounding the Ton Le Sap in Cambodia. The landscape of such plains is flat and the sediments are usually clayey but may be fine-layered at some depth (varved sediments), representing recurrent peaks of flooding and sedimentation in the lacustrine environment.

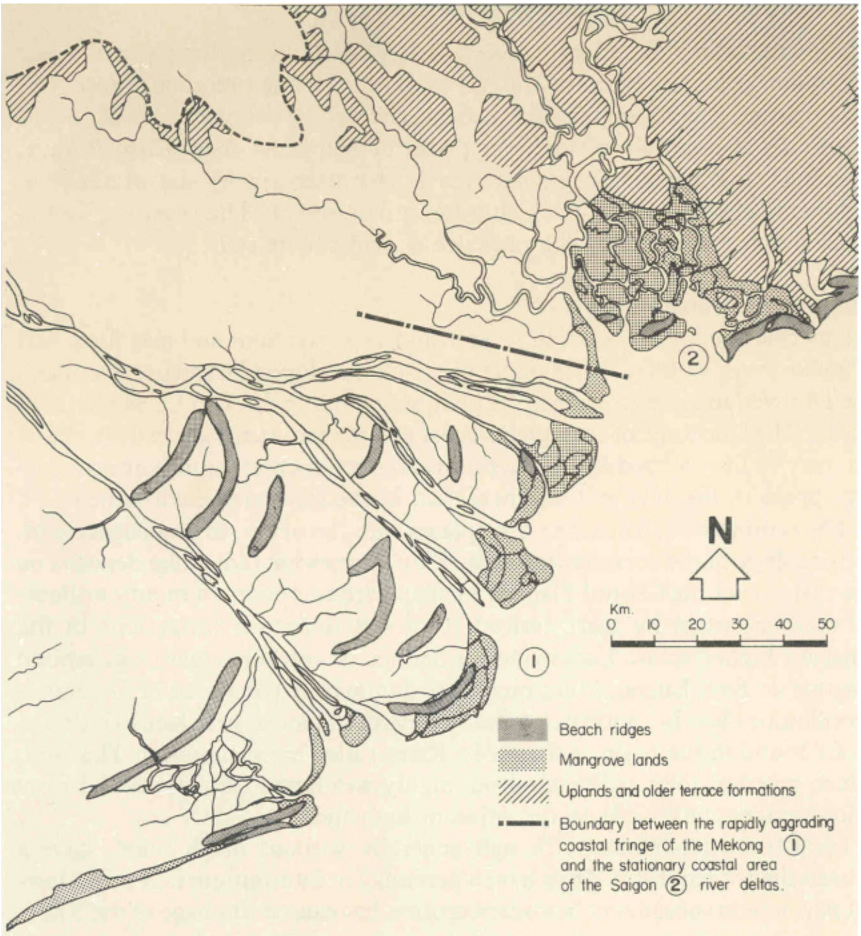
The sediments in lacustrine floodplains vary, however, in accordance with the lithology of the surrounding area. Thus, somewhat older lake deposits on the east side of the Central Plain of Thailand are composed of montmorillonitic clay underlain by marl derived from soft limestone formations in the adjacent higher areas. Lacustrine formations in volcanic areas (e.g. around Laguna de Bay, Luzon, Philippines) are dominantly composed of fine montmorillonitic clay. In contrast, kaolinitic clays dominate in such lacustrine areas as are found in the basin of the Moon River valley in northeastern Thailand, which received their sediments from highly weathered formations and from acidic sedimentary rocks in the adjacent highlands.

Lacustrine floodplains, although generally without much relief, have a saucer-shaped landform. Most have a perennial or intermittent lake in the lowest part unless subsequent landscape erosion has caused drainage of the lake.

Marine floodplains

In the coastal lowlands of' the rice-growing area, two broad landscapes can be distinguished. The first type is that of the rapidly aggrading coastal plains found in the lower deltas of many minor and major rivers. These are broad clayey plains, mostly separated by consecutive sandy beach ridges, and without a dendritic tidal creek system. An important aspect of the rapid growth of this type of coastal plains is that the accumulation of pyrite (FeS_2) under mangrove vegetation is restricted, and such plains have few acid sulphate soil areas.

Rapidly aggrading coastal plains are found mainly in the lower delta areas of river systems with a considerable sediment load and with shallow coastal waters (continental shelves). A typical example of a rapidly aggrading lower delta is that of the Mekong River system in Vietnam (Fig. 10). The coastal plain, characterized by sediments deposited in a marine saltwater environment, has a maximum width of more than 100 km between the Bassac and Cua Dai branches. This plain is composed mainly of recurrent low sandy beach ridges



10. Part of Vietnam showing the aggrading coast of the Mekong River (1) and the stationary coast of the Saigon River (2).

and wide intermediate plains dominated by clayey sediments. The river branches and their associated creeks have low or no levees, and there is little gradation in texture of the sediments from the rivers and creeks toward the interior. Thus, the levee-basin pattern of the interior river plains is absent in these coastal plains, which are flat and featureless, and are interrupted only by a limited number of lower depressions in which the creeks flow.

The second type of landscape in the coastal lowlands is the slowly aggrading or stationary coastal plain. Such coastal plains are characterized mainly by broad mangrove zones and relatively little development for rice land. The tidal land is cut up by numerous winding tidal rivers and creeks, and sandy beach ridges are either absent or rare. The estuary of the Saigon River (Fig. 10) is a typical example of a stationary coastal plain.

Stationary or slowly aggrading coastal plains are found mainly in the deltaic areas of rivers with a low silt load. Many of the equatorial coastal plains are of this type, e.g. the coastal plains of Sumatra and Kalimantan in Indonesia, where the low coastal areas are composed mostly of peat. Another type of relatively stable coastal plain is that of the Sunderbans in India (Bengal) and Bangladesh, where the coastal landscape undergoes a continuous subsidence and mass movement because of the presence of a deep trough (so called *swath of no ground*) in the sea bottom close to the coastline. In such a case aggradation of the coastline is slow, even though the sediment load of the rivers may be high. Variations of the coastal plain pattern are found in the stationary plains in the drowned river estuaries along the southwest coast of West Africa where growth is slow and where a stationary mangrove zone is present.

Much of the coastal land with a stationary coastline remains unreclaimed. Where it has been reclaimed for rice growing, as in the Sunderbans, the rice land usually has more or less severe hydrological and soil problems. The latter are related to the long period that such lands are under a mangrove vegetation, which results in a high accumulation of organic matter and of pyrite and leads to acidification of the soil (acid sulfate soils) after drainage and reclamation.

Alluvial terraces

Alluvial terraces are former river, lake, or marine floodplains that, because of a relative lowering of the base level of drainage, are above the level of regular flooding. In some cases alluvial terraces are formed by orogenetic lifting of blocks of the landscape (uplifted peneplains). But most alluvial terraces of the major rivers and coastal plains in rice-growing areas are related to changes in the base level of erosion, corresponding to cyclic climatic changes in recent geological times.

Most of such terrace areas have a gentle gradient, and seen over larger surfaces are predominantly flat to gently undulating. All major and most minor river floodplains are accompanied by river terraces, with an almost level or slightly undulating topography. The rice-growing area on alluvial terraces is considerable in the major river basins of Southeast Asia. For the Chao Phraya basin in Thailand, Fukui (1971) estimated that 40% of the paddy lands are found on river terraces and their associated alluvial-fan complexes. In the lower Mekong basin, except the present delta, which is mainly in Vietnam, the proportion is even higher in favor of the river terraces. Considerably more than 90% of the rice in that area is grown on the river terraces, mainly in the lower swales of the late Pleistocene *low terrace.*

Some flatter parts of older Pleistocene terraces, the so-called *middle terrace,* are also in use for rice growing under a rainfed regime in bunded and leveled paddy fields. Rice is grown extensively on the Mekong terraces, especially in northeast Thailand, and also on the Vientiane plain in Laos, the area surrounding Ton Le Sap in Cambodia as well as parts of the low terrace areas east of the Mekong in southeastern Cambodia, and in Vietnam.

Other major rivers in South and Southeast Asia have comparable areas of river terraces, the lower portions of which are in use for rainfed paddy land. Of less importance for rice growing are the marine terraces, which can be found adjacent to the present deltas and in strips of varying width along many coasts.

Low river terraces, with conditions more or less favorable for rice growing in terms of rainfall, accompany most other rivers in the world's rice-growing belt. Typically, however, their extension relative to the higher land is less favorable than in the major rice-growing areas in Asia. Africa's Niger River and its tributaries, for example, have a narrow floodplain and their accompanying level terraces are not extensive. Nevertheless, rice growing has expanded considerably on the Niger terraces in the last 10 years.

Terrace landforms vary strongly according to age and erosion base level. The most recent terraces — those that have barely ceased to be part of the active present-day floodplains — show all or most of the characteristics of active alluvial plains. However, no river or marine flooding occurs on them so that rice lands, unless irrigated, are basically dependent on rainfall.

Older and relatively higher terraces are dissected to a varying degree. Where dissection has progressed significantly, the landscape has become undulating to rolling and the terrace is no longer part of the rice-growing lowlands. Between completely dissected older terraces (mainly lower Pleistocene) and the nondissected, semirecent terraces, all intermediate forms are found.

A characteristic type of valley incision is observed on terraces composed mainly of unconsolidated, permeable sediments as, for instance, the fan terrace complexes of the footslopes of volcanos of the Philippines and Java. There, the flat summit areas used for rainfed or irrigated rice are maintained intact while a deep gorge-like erosion takes place at the site of rivers and lesser drainageways. In other formations, the erosion pattern is of a more lateral nature, with wide shallow valleys giving a more undulating aspect to the landscape. That is the case in the wide low terrace areas of northeastern Thailand.

Various forms of dissection of the terrace areas in Bangladesh have been described by Brammer (1971b). Dissection of the Madhupur and Barind terrace tracts has resulted in four major forms:

- level, poorly drained areas, with meandering streams about 9 km apart;
- flat summit areas, with deeply cut valleys and dissected gullied land bordering the valleys;
- areas of deeply weathered terrace formations crossed by broad and wide shallow valleys, most of which are streamless, although considerable areas remain wet as a result of damming of valleys; and
- areas of shallowly weathered terrace formations. dissected by a close network of small, branching, streamless valleys.

These examples indicate the complexity of landforms that are found on alluvial terraces.

CHAPTER 3

The hydrology of rice lands

TYPES OF RICE LANDS IN FUNCTION OF WATER REGIME

Rice grows on a wide range of landforms affected by an equally wide range of hydrologic conditions, which reflect in the often confusing terminology that has evolved to characterize such conditions. Identical sets of conditions are often known by a score of names, many borrowed from local languages. Seemingly general terms such as *upland rice* or *riz pluvial* cover quite divergent land conditions that are, unless specified, of limited value at best or confusing at worst.

The term *upland rice* has been defined in various ways. In its limited sense it is rice grown on nonbunded, nonleveled fields that are prepared and seeded dry and depend on rainfall for moisture. In West Africa, upland rice is all rice grown in nonflooded fields, including those where shallow groundwater is the major source of moisture. But West African rice may be transplanted, as in eastern Nigeria, and still be considered upland.

Other uses of the term upland may include lands that are bunded and rainfed, as in the relatively high-elevation paddy fields in Orissa, India, and other parts of Asia. Yet many publications specifically exclude such rice lands from the upland terminology.

Similar difficulties arise with other generally familiar terms used to characterize the environment in which rice is grown — *lowland* rice, *swamp* rice, *hill* rice, *plateau* rice, etc.

The general use of terms such as *upland* rice and *irrigated* rice, although understandable, is semantically and technically incorrect. Such use implies different kinds of rice, possibly even genetically different, for the landforms that are inferred by the terms. These are not different rices in most cases. While there certainly are varietal adaptations to environmental conditions, it is normal to find that varieties can grow under different conditions, and identical varieties are grown in nonflooded, partially flooded, or continuously flooded fields.

It is obviously advisable to replace the crop-oriented terminology with land-oriented terms. In this respect, a number of classifications, both local and international, have been proposed but they are neither satisfactory nor complete. Rice grows as a dryland crop like any other cereal crop, or it can grow while inundated during most of its growing cycle. In between are intermediate conditions, including possible transitions from one condition to another during a growth cycle. Moreover, human action, which includes ponding water, irrigation, and drainage, is an important factor that influences the variation in conditions for rice growth.

The general requirement is for a classification of rice lands that recognizes

- the topographical position of the rice land as related to hydrological conditions,
- the natural sources of water supply for rice land, and
- the possible modifications in the natural system by human action in both the topography (micro) and the manipulation of water.

The terms upland, hill, plateau, and lowland used to characterize rice fields are related primarily to topographical position. Swamp, deep-water, and rainfed (pluvial) indicate the natural source of water supply. Terms like bunded paddies and irrigated rice lands imply modifications in the water regime by human action.

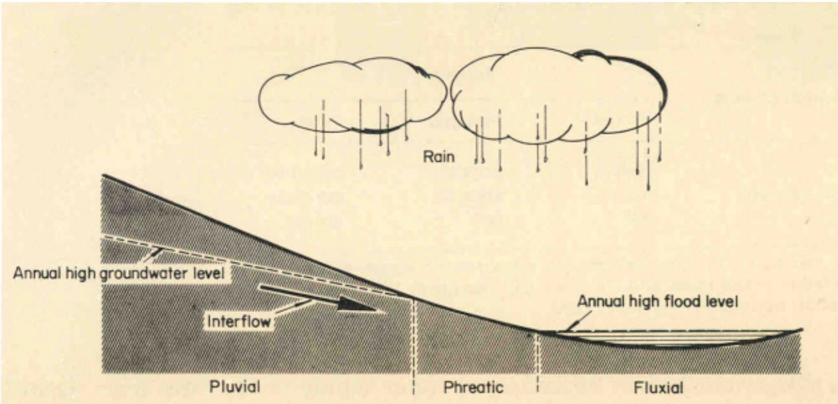
It is understandable that a terminology based on the indiscriminate use of one or two of these general terms leads to confusion and overlap.

Landscape positions

Landscape positions of rice lands where no artificial changes in topography and water supply have taken place are indicated schematically in Figure 1. This model is valid, with local modifications, for most rice lands in Africa and South America, where man-made changes in the topography of rice lands and manipulation of the water supply are the exception. But even in Asia, the three physiographic-hydrologic positions of rice lands can usually be easily recognized, even though the influence of the positions on the actual hydrologic conditions in the rice fields is often overshadowed by bunding and leveling, puddling, and irrigation.

PLUVIAL RICE LANDS. Water for rice plants on pluvial rice land is exclusively from rain. Excess water leaves the soil by percolation or as runoff. In the landscape, pluvial lands occur on gently-to-steeply sloping terrain and at relatively high levels in respect to the levels of groundwater or surface water. Soils of this category have, under natural conditions, a free drainage with no, or only weak, signs of periodic water saturation of the profile.

PHREATIC RICE LANDS. In phreatic rice lands, rice plants are fed by rainwater and by groundwater (phreatic water), which is at a shallow depth during at least part of the crop season. Excess rainwater leaves the field as runoff and phreatic rice lands are never flooded for more than a few hours during or after heavy rainfall. Locally, phreatic lands may receive some runoff water from higher portions of the landscape during heavy rains. In the landscape, phreatic



1. Classes of rice land according to topography and water supply.

rice lands commonly occur on foot slopes and in that case periodically or continuously high groundwater is mainly caused by lateral subsurface flow of groundwater, or *interflow* (Fig. 1). Spring levels, which occur higher in the landscape, will locally cause similar conditions; thus phreatic rice lands are sometimes found at relatively high elevations and on steep slopes. On the other hand, they also occur in valley and plain positions where natural retention of surface water is nil because of a distinct gradient of the surface, or where their position is above the natural flood level.

Phreatic rice lands also are found on level and relatively high aspects of the landscape where impervious layers in the subsoil cause the formation of a temporary, suspended water table in periods when rainfall exceeds evapotranspiration and runoff. In such cases, lateral inflow of groundwater usually plays a minor role.

Soils of the phreatic rice lands category show, under natural conditions, signs of temporary water saturation (gley mottling) in the profile, usually starting at a shallow depth.

FLUXIAL RICE LANDS. As defined here, fluxial rice lands receive water wholly or partly from surface flow — runoff, water from streams, etc. In their natural state, fluxial rice lands are inundated for at least part of any year during which a rice crop is grown. Landforms in which fluxial rice lands occur are always in the lower parts of the landscape, as in valleys or closed depressions. Drainage, whether internal by percolation, or external by runoff, is sufficiently slow so that rice fields remain flooded for at least part of the time that rice is grown. It is difficult to delineate time of flooding but its cumulative duration is long enough to exclude the growing of major upland or dryland crops in most seasons when inundation occurs. On the other hand there is no standing water, for at least part of the year on fluxial rice lands.

Table 1. Sources of natural water supply to three categories of rice lands.

Source of water	Supply		
	Pluvial	Phreatic	Fluxial
Rain	always	possible [a]	possible [a]
Subterranean	no	always	possible
Surface	no[b]	no [b]	always

[a]No rainwater or, more seldom, no subterranean water, is received by rice fields in the most arid climates, e.g. the lower Nile valley. [b]Except for short periods during heavy rain.

Table 1 summarizes the source of water supply of the three main *natural* categories of rice lands.

Modification of the natural water regime

Pluvial and phreatic rice lands are not, or are only briefly, inundated in areas where there is a low level of land and water management for rice. This is the case for most rice-growing areas in the tropical zone outside of Asia. One of the most fundamental aspects of the Asian type of rice cultivation is the advanced level of water conservation on rice fields where prolonged natural flooding does not normally occur.

Modification of the natural water regime toward a more aquatic regime basically involves two management practices:

- The leveling and bunding of individual fields, which leads to retention or ponding of water. Such leveled and bunded rice fields are designated as paddy fields.
- Irrigation of rice fields, either by water brought in from elsewhere or by overflow from a higher to a lower paddy field.

The advantages of growing rice in an aquatic milieu are several, and their relative importance is locale specific in that each advantage operates to a varying degree depending on soil, climate, hydrology, soil fertility, biotic factors, etc. A few advantages, however, seem to operate in most circumstances:

- Sufficient water supply for the rice plant, which among food crops is one of the least drought-resistant plants.
- Ease of land preparation in moist to wet soils, especially when only hand tools or simple animal-operated equipment is used. This factor is important in the dominantly clay paddy fields of Asia.
- Simplified weed control by wetland preparation and flooding. Only a limited number of weed species can grow and compete with rice under flooding. Weed control is a major problem on nonflooded rice lands, e.g. on the phreatic rice lands in West Africa.
- Greater availability of plant nutrients. Under flooding more nitrogen is supplied to the soil, mainly because of biological nitrogen fixation. This is the

main reason that rice grows year after year in paddy fields without application of fertilizer nitrogen. Phosphorus becomes more available after a soil is flooded as do several minor elements with the noticeable exception of zinc. While this enhanced availability of plant nutrients is generally an advantage, other phenomena in flooded and reduced soils may negate the positive effects of an aquatic milieu in this respect.

The Asian technique of bunding and leveling land for rice cultivation increases the capacity of the land to retain water by limiting runoff and by storing surface water. Bunding and leveling on sloping land constitute an advanced method of erosion control. It is indeed remarkable that little erosion takes place in paddy lands on soils that are subject to severe sheet and rill erosion when cultivated in their natural state.

The importance of the construction of paddy fields for soil conservation is vividly demonstrated in rice-growing valleys in the dryland zone of Sri Lanka. Within those valleys water is often ponded in a series of consecutively lower tanks (artificial reservoirs). Between the tank areas, the land is leveled and bunded for rice crops, thus avoiding erosion and silt transport. No measurable silting of the tanks has taken place. The situation changes, however, where between-tank side slopes are used for dryland crops as has happened in many areas of southern India. There, sheet erosion on the watersheds of the tank areas has caused silting of many of the tanks.

Paddy fields serve as a sediment trap when flooded by silt-containing water. In some cases, as in the Banaue terraces of northern Luzon, the increased sedimentation is harnessed and used to build terraced fields.

Whether pluvial and phreatic rice lands are leveled and bunded depends on topography, soil conditions, and availability of water, as well as on economic and cultural factors. For instance, in the traditional agriculture of most of Africa, farmers avoid use of periodically wet lands, a pattern also followed with the more recently introduced rice crop. In Asia there are farmers who, partly for religious reasons, grow rice exclusively on swiddens even though they are familiar with rice cultivation on ponded fields and have some land suitable for wet cultivation (Conklin, 1957).

An artificially induced aquatic regime on pluvial and phreatic rice lands can be indicated by the addition of the word *anthraquic* to the terms pluvial and phreatic. This term is a contraction of *anthropic* indicating the man-made aspect, and *aquic* related to *aqua,* the Latin word for water. Adding anthraquic to the term fluxiai makes it redundant because fluxial rice lands are by definition aquatic for part or most of the growing season.

Management factors sometimes cause a shift from pluvial or fluxial to phreatic land. For instance, leveled and bunded fields that receive much water from irrigation or seepage may become water-saturated to great depths and change from pluvial anthraquic to phreatic anthraquic. Likewise large-scale flood control measures may cause rice lands to shift from the fluxial to the phreatic category.

WATER IN PLUVIAL RICE LANDS

In pluvial rice lands that are not leveled or bunded, water availability in the root zone of the rice crop is determined by

- climatic factors, mainly those related to rainfall;
- inherent soil characteristics;
- soil management factors; and
- varietal characteristics of the rice as regards use of the soil water.

We give primary attention to the first two factors, and deal with other factors only as they relate to climate and soils.

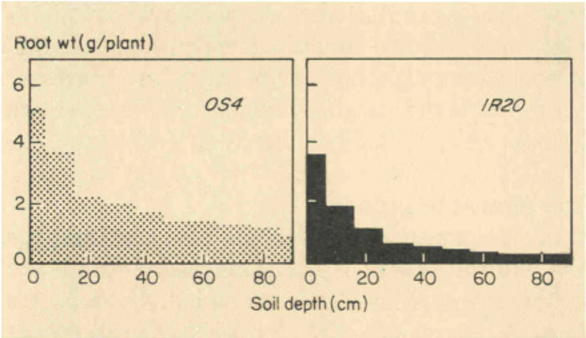
Climatic factors

On pluvial rice land, the main yield-determining factor is the nature of the rainfall. Total effective rainfall is important, but it is overshadowed by the influence of rainfall distribution.

An important factor in the plant-water relationships of rice grown on pluvial rice land is the rooting depth of the rice plant. Compared to other dryland crops, rice has a restricted effective rooting depth — the depth from which it can extract water for both survival and grain production. Rice relies on the moisture in that portion of the soil profile that is the first to lose its available water by evaporation.

Rice varieties differ considerably in resistance to drought stress, and there is an extensive effort to breed varieties that are highly resistant to drought. In terms of soil-water relationships, higher resistance to drought would mean that the resistant varieties either are more deep rooted, or more efficiently extract the water from the soil, or both. Studies in this respect reported, among others, by Le Buanec (1975) and IRRI (1977) indicate that rice varieties adapted to pluvial conditions have more roots at greater depth (Fig. 2). The total number of roots does not appear to be higher for drought-resistant varieties, but they have more roots at a 20-cm depth than varieties that are commonly irrigated. Research on sandy soils at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria (Moormann et al., 1977), indicate that certain drought-resistant varieties extract more water from the soil than nonresistant varieties, and can withstand longer periods of drought stress.

Low supply of soil moisture is generally the most serious factor limiting rice production. Rice on pluvial rice land needs at least 600 mm of rainfall to complete its growth cycle (Cochemé, 1971), provided that the rain is distributed evenly. For Latin America, Brown (1969) reports 1,000 mm of annual rainfall with a monthly rainfall of 200 mm during the growing season as a minimum requirement. Le Buanec (1975) lists rainfall for various zones of dryland rice cultivation in Asia, Africa, and South America. He reports that while in some areas annual rainfall is as low as 1,000 mm, rice cultivation is most widespread in regions with more than 1,500 mm. In general, conditions for growing dryland rice appear to be submarginal where annual rainfall is less than 1,000 mm,



2. The dryland variety OS4 has a heavier, deeper root system than the wetland variety IR20 (IRRI. 1977).

marginal between 1,000 and 1,300 mm, and fair with between 1,300 and 1,600 mm. At more than 1,600 mm, rainfall ceases to be a major constraint. These figures are not absolute; they are modified by factors such as rainfall pattern and distribution, rate of evapotranspiration, and soil properties.

The general rainfall pattern and the duration of the wet season become most critical for areas with a low annual rainfall. This is the case when there is a marked dry season between two annual wet seasons. In such zones of bimodal rainfall, annual rainfall as high as 1,300 mm is considered submarginal and dryland rice cultivation can be recommended only for areas with more than 1,500 mm annual rainfall.

Daily rainfall distribution is of great importance to the productivity of pluvial rice lands. Where rain during at least part of the growth cycle of rice comes in clusters of heavy rainstorms — with marked dry periods between — conditions are unfavorable. A large part of those rains is lost by percolation and runoff, and the intermittent, irregular, rainless periods between storms may cause drought stress, yield loss, and even total crop failure.

Drought periods of 20 days or more are usually damaging to a rice crop, but the exact critical duration depends on many factors including soil and soil management, growth stage of the plant, and rice variety. Drought occurs regularly in areas with extensive dryland rice cultivation, such as in West Africa and Brazil. Even areas with a monomodal annual rainfall of 2,000 mm or more are not free of recurrent, damaging drought periods. The unpredictable occurrence of drought and the consequent yield loss, which is more serious for rice than for most other food crops, is the main reason for the movement toward hydrologically better lands for rice growing in South America and Africa. In southern Senegal, for example, rice production on phreatic rice lands has increased while it decreased on higher lands, even though the higher lands are more fertile (Bertrand, 1973).

Most of the data on minimum rainfall requirements for rice come from the relatively new rice-growing areas in Africa and South America. In the rice-growing areas of Asia, rice on pluvial lands is found mostly in high rainfall areas, and marginal conditions in respect to rainfall are avoided. Only where increasing population pressure exists, as in certain parts of India, is dryland rice grown in the marginal rainfall areas. Yields in such cases are low (less than 1 t/ha) and crops fail completely in dry years.

Soil characteristics

There is a paucity of data relating the water-holding capacity of freely drained soils and the growth of rice. This relationship is probably most important in areas of marginal and uncertain rainfall, but it plays a role even in high rainfall areas. A general idea of the influence of a soil's water retention characteristics on the performance of the rice crop may be obtained by study of the distribution of pluvial rice lands in function of the kind of soils. Thus, sandy soils with a low organic matter are not often used for dryland rice because of their poor water retention and poor fertility, even in the high-rainfall areas.

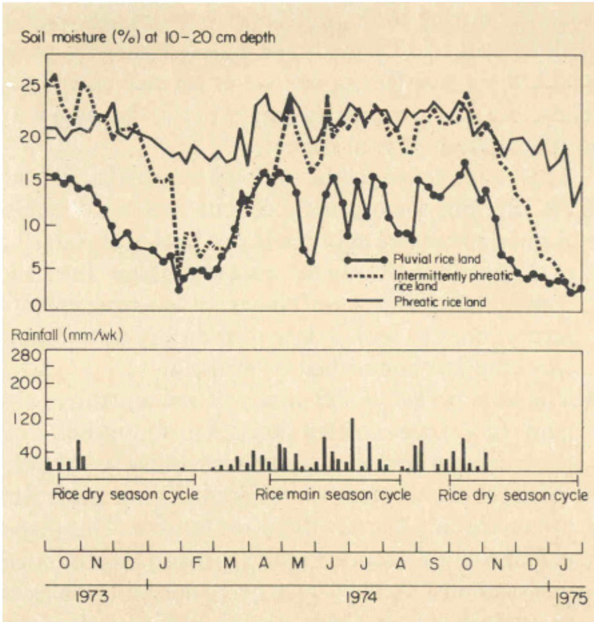
Mainly because of their good water-holding capacity, deep soils derived from the more basic parent materials are favored for dryland rice growing in the monsoonal areas of continental Southeast Asia. Soils of this nature derived from limestone, basalts, volcanic ash, and certain shales are preferred for rice grown as a dryland crop on plateaus and in hills. Most of these soils have a relatively high organic-matter content, a favorable microporosity, and a stable structure. Their water-holding capacity is favorably influenced by the specific clay mineralogy. While low rice yields occur on such soils in dry years, any drought is much less severe than that on soils in the same general area with less favorable physical and mineralogical characteristics, e.g. those derived from the more acidic rocks or those formed on medium-textured, old, alluvial sediments.

In soils freshly reclaimed from forest or bush fallow, organic matter content, useful porosity, and the available-water holding capacity are relatively high. However, after 1 or 2 years of cultivation, those favorable parameters deteriorate and rice becomes more subject to drought stress. This is particularly true for the sandy soils and it is a prime reason that projects for permanent use of such lands for annual crops, including rice, often fail in areas with uncertain rainfall.

WATER IN PHREATIC RICE LANDS

Phreatic rice lands that are not leveled and bunded are scarce in the rice-growing areas of Asia; such lands are almost without exception anthraquic. But nonleveled, nonbunded phreatic rice lands are common in newer rice-growing areas outside of Asia, particularly in West Africa and in parts of Latin America where there is a strong tendency toward the increased use of such land for rice.

Water availability in the root zone during the growing cycle in phreatic rice lands is influenced by the same parameters as pluvial rice lands, i.e. climate,



3. Soil moisture content in the root zone of pluvial and phreatic rice land at the International Institute of Tropical Agriculture, Ibadan, Nigeria.

inherent soil characteristics, and soil management. However, the availability of additional water in the root zone, related to high groundwater during at least part of the growing season, profoundly alters the suitability of the land for rice. The difference between pluvial and phreatic rice lands is illustrated in Figure 3 (Moormann et al., 1977). These data pertain to a long-term experiment at IITA on a toposequence that ranged from well-drained to poorly drained. The higher area of the toposequence is equated with pluvial rice land and the lower area is continuously influenced by water flowing laterally at shallow depth (interflow water). The intermediate area is subject to high groundwater only in the wet season. The low and intermediate areas are phreatic rice lands, because in both cases interflow water is available in the root zone, which is represented in the figure by the soil layer at a depth between 10 and 20 cm.

The dynamics of soil moisture in the pluvial portion of the experimental area illustrate what happens in a marginal rainfall area such as Ibadan (1,240 mm annual rainfall) with a fairly poor distribution of the rainfall. No rice can be grown there in the dry season, and prolonged dry periods in the wet season (May-June and August 1974) cause drought stress and yield loss because soil moisture in the root zone drops below the critical level.

In the phreatic portion of the experimental area, rice will grow with considerably less drought risk. The lowest, most hydromorphic area can be used throughout the year for rice without risk. In the intermediate area, dry periods do occur during the rainy season but soil moisture does not drop below the critical level. Additionally, in this temporarily phreatic zone the period in which there is sufficient soil water for rice extends well into the dry season. Therefore, the growing season for rice in this area is 1 to 2 months longer than in the adjacent pluvial zone.

This example is specific for local weather, soil, and water conditions at the IITA site, but some general conclusions are possible:

- A main advantage of phreatic rice land over pluvial rice land is the reduction of drought risk during the growing season. Even though the available water content in the root zone follows, to a varying extent, the general rainfall pattern, it does so with a delay during dry periods and harmful effects on the rice crop are diminished or avoided.
- The total period of sufficiency of soil moisture is increased in phreatic rice land. In a climate with a short (3 to 4 months), but fairly wet rainy season, the increased period of water availability in phreatic lands makes them suitable for rice, whereas the adjacent higher lands with pluvial conditions are not or are only marginally suited for rice. This disposition governs to a large extent rice production in the Sahel and Sudan zones of Africa. There, rice is grown almost exclusively in hydromorphic swales and valleys where shallow groundwater is available during and after the rainy season.

  In zones with a longer rainy season, two successive rice crops may be grown on phreatic land; however, this is not done in the phreatic rice-growing areas of Africa.
- The importance of the soil's water-holding capacity tends to diminish in phreatic rice land. While for reasons related to plant nutrition, medium- to fine-textured soils are more productive than sandy soils in phreatic areas, the poor water-holding capacity of sandy soils plays a lesser role if sufficient groundwater is available. This may be seen among other places, in southern Senegal (Casamance) where the sandy hydromorphic soils of the valleys are preferred for rice growing even though the less sandy soils of the uplands have better water retention and better fertility.

The behavior of shallow groundwater is anything but simple and, moreover, has not been adequately studied in relation to field conditions. While much work has been done on the overall hydrology of catchment basins, the moisture behavior of groundwater in the shallow surface layers that form the root zone for rice plants has hardly been studied. Certain data may be drawn from detailed soil survey investigations, inasmuch as temporary shallow groundwater is reflected by the presence of the gley phenomenon in soils (grayish color of the soil matrix and rusty mottling). However, such properties of the soil profile are not necessarily a sufficient guide to the degree of hydromorphism of soils because they do not indicate how long and to what degree the soils remain wet. On the other hand, soils may have temporary high groundwater without showing the gley phenomenon. This is often the case in tropical soils. Profile study alone is therefore not sufficient to determine the degree and the dynamics of hydromorphism of phreatic rice lands. Detailed studies that link the performance of the rice crop with the behavior of groundwater and interflow are needed. Examples of such studies are those in Senegal by Bertrand (1973), and in Nigeria by Moormann et al. (1977).

WATER IN FLUXIAL RICE LANDS

Fluxial rice lands occur in valleys, swales, and closed depressions, and on floodplains with slopes that seldom surpass 1%. Such lands flood because of a periodic excess of surface water in combination with limited drainage. Fluxial rice lands always occur in the lower aspects of the landscape. In medium- to high-rainfall areas, the lowest parts of inland valleys are occupied mostly by fluxial rice lands as are most of the basins or backswamps of meander river plains. Flooding in fluxial rice lands varies considerably in depth and duration. Only the most common flood regimes are discussed here.

When fluxial rice lands are not flooded, water availability is guided by the same factors as in pluvial and phreatic rice lands, which relate to the availability of rainwater and groundwater. Parameters guiding availability of floodwater are dependent to a large extent on the rainfall pattern and runoff from the catchment areas in which fluxial rice lands occur. Copious rainfall in the upper river basins may produce prolonged and deep flooding in the lower meander plains, while for inland valleys, depth and duration of flooding are affected more by the rainfall in the immediately adjacent highlands. This means that in the wide lower plains the time of flooding and the availability of floodwater for rice are more predictable.

Nevertheless, flooding is not always a predictable and dependable source of water for rice growing. In the arid zones, especially, fluxial rice lands may suffer from drought if rains fail in the catchment areas, as is often the case in the valleys of the Senegal and Niger River basins in the Sahel zone of Africa. Unless such fluxial rice lands are irrigated, their water regime is comparable with that of phreatic rice land, or even sometimes of pluvial, during part of the time that rice is grown.

Flooding in fluxial rice lands may he detrimental and can cause crop losses. That is commonly the case in inland valleys when a closely spaced series of unusually heavy rainstorms occur. The standing rice crop may be physically damaged, young rice plants may be uprooted or drowned, and land may be damaged by scouring.

HYDROLOGY OF BUNDED AND LEVELED RICE FIELDS

Bunding of rice lands, and its collateral leveling of sloping land, bring about a considerable change in the water regime of that land. The overall effect is that runoff water is diminished and more water, whether from a natural source or from irrigation, or both, is retained on or in the soil. Bunding and leveling of land for rice make a near perfect measure of water conservation.

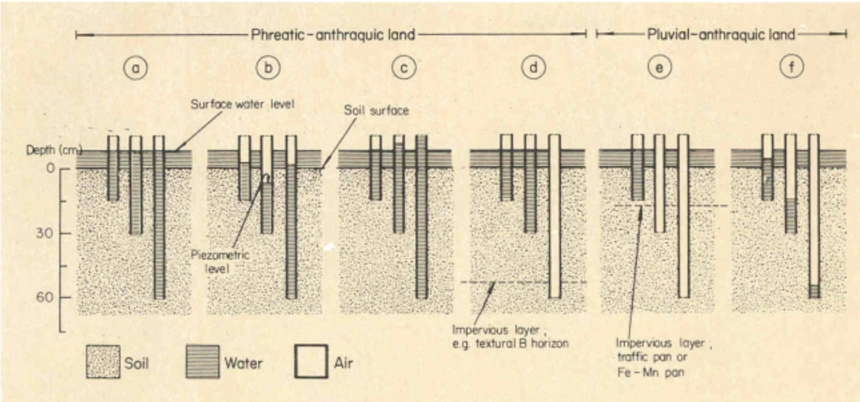
This method of water conservation is an essential part of the Asian type of rice cultivation and has been for centuries, even to the point that steep slopes are often terraced to make water retention possible. In areas of marginal rainfall, with soils that have a moderate or even low water-holding capacity, rice can grow on rainfed bunded paddy lands; however, cultivation under pluvial or phreatic conditions would be marginal or impossible. The practice of bunding and leveling to create an aquatic environment in rice fields in Asia has permitted rice growing in areas beyond the crop's natural ecological boundaries.

In areas where rainfall is marginal for rice growing, bunding and leveling of the dry land are by themselves not sufficient to guarantee an acceptable yield. Le Buanec (1975) in describing what he calls the *Indian system* of rice cultivation states that the technique of bunding and leveling for pluvial rice lands in dry areas such as Uttar Pradesh, Madhya Pradesh, and Gujarat is only an imitation of methods used in more favorable environments, and is without any appreciable benefit. This is not true, even for marginal rainfall areas, but the fact remains that prolonged drought in bunded, leveled paddies leads to partial or total crop failure if' no water from outside is available.

Most studies dealing with water in aquatic rice fields have focused on the various aspects of water use and little attention has been paid to the behavior of water in the soil. Many researchers working with rice take it for granted that when the field is flooded the soil is necessarily saturated with water to a considerable depth. While this is true in many phreatic rice lands. e.g. in perennially wet, low-lying areas and in young, highly permeable marine clay soils that were recently reclaimed from mangrove swamps, it does not apply to pluvial rice lands and to the majority of the fluxial rice lands.

In most wetland rice soils only a 10- to 30-cm thick surface layer is saturated during the growing season and sometimes the soil is barely moist, or even dry, between the saturated surface layer and the zone influenced by groundwater, which may be at depths varying from less than a meter to tens of meters. This can readily be demonstrated by boring a hole in a flooded field while protecting the hole from surface water. Generally, it will be found that an auger hole will remain dry in the upper zone and that water, once it appears at a certain depth (often somewhere between 50 and 100 cm), rises into the dry layer but normally does not reach the soil surface. This phenomenon was described for a wide variety of paddy soils from Malaysia (Phillis, 1963) and we have observed it at many other sites.

Similar observations using permanently installed open-ended pipes (piezometers) placed vertically in auger holes were reported in anthraquic rice lands in the Philippines (Kampen, 1970), in Taiwan (Chen et al., 1969), and from recently reclaimed coastal marshes in Surinam (Scheltema, 1974). The behavior of water in the soil as described by those authors is discussed with



4. Various. hydrologic conditions in flooded rice fields, illustrated by sets of three piezometers placed at different depths.

reference to Figure 4, which shows sets of three piezometers inserted to various depths in different situations.

In Figure 4a the water leveIs in the three piezometers are the same, and equal to that of the surface water. The soil is completelysaturated to at least a 60-cm depth. One may expect that if the water level in any of the piezometers is disturbed by adding or removing water, the original level is reestablished quickly, i.e. the permeability of the soil is high throughout. This situation is typical for highly porous soils of coastal marshes recently reclaimed for rice cultivation (Scheltema, 1974) and also for soils that are high in organic matter.

Wjthin 10 years after the start of cultivation of predominantly mineral coastal marsh soils in Surinam, the permeability of the soil between 20- and 50-cm depth decreased strongly because of the collapse of the larger pores. Also, removal by the rice plant of water,from the highly impermeable puddled surface soil was more rapid than supply from the water ponded on the field, which lowered the water level in piezometers placed in the root zone (Fig. 4b). In puddled (but not in dry-tilled) soil the piezometers in the root zone even became fully drained within 4 weeks of planting rice while water was present on the field. The water level of the deepest piezometer was often higher than that in the surface soil, indicating a tendency for upward movement into the root zone. Despite the slow permeability of the upper 50 cm of the soil, changes in the level of the surface water were reflected by the water levels in the piezometers placed in the still highly permeable subsoil. This indicates that some connection existed between the floodwater and the deeper groundwater, presumably through occasional cracks or channels in the soil mass.

Although the details given immediately above may be typical only for young soils in coastal areas, the situation depicted by Figure 4b was also observed in low-lying riverine irrigation areas in the Philippines (Kampen, 1970).

5. Water seeping from adjacent highlands causes positive hydraulic pressures (measured in the piezometer, lower land) and wet soil conditions throughout the year as in this phreatic-anthraquic rice land in an inland valley of Sri Lanka's wet zone. Nutritional disorders that cause poor rice growth in such land are discussed in Chapter 6.

In depressed areas bordering high land, a permeable stratum may carry artesian water that can sometimes be tapped to serve as a free-flowing well. A less extreme case is illustrated in Figure 4c, and seen in the field in Figure 5.

In sandy paddy fields, e.g. as in northeastern Thailand, early rainwater percolates rapidly until it stagnates on less permeable layers in the subsoil. Piezometer levels in such conditions might be as indicated in Figure 4d. Permeability for water in the surface soil is rapid enough to maintain identical water levels in the shallow piezometers while water penetrating the impervious subsurface horizon is insufficient to build up to any level in the deepest piezometer.

In these soils, saturation of the surface layers occurs after considerable rain has fallen, and only then can rice be transplanted. The depth at which less permeable layers occur in the sandy soils of northeastern Thailand is critical in function of total rainfall. In low-rainfall areas (Khon Kaen) no rice paddies are found when the thickness of the permeable sandy surface layer exceeds 50–60 cm, but in higher rainfall areas (Ubon) the thickness may be more than 100 cm.

The situation in Figure 4e is common in originally well-drained pluvial land that has become anthraquic as a result of bunding, leveling, and the formation of a traffic pan, and sometimes as a result of an accumulation horizon of iron and manganese oxides. A perched water table is present at a shallow depth and the subsoil is dry or moist.

If the subsurface horizons are more permeable, a situation as depicted in Figure 4f occurs. Free groundwater may be present at greater depth, but unless that water is artesian there is a considerable hydraulic gradient permitting vertical downward movement of the surface water.

It should be realized that hydrologic conditions often vary within a single paddy field. This is especially true in sloping areas, where upwelling of water may take place adjacent to a higher field and downward movement occurs adjacent to a lower field (see Chap. 6, Fig. 14).

In most bunded and leveled rice fields with fine loamy or finer soils, an intermittent suspended water table in the surface horizons distinguishes such rice lands clearly from the nonbunded pluvial and phreatic rice lands. The main reason for the formation of suspended temporary water tables in such lands is that loss by percolation is slower than the accumulation of water from whatever source in the paddies. Surface ponding occurs in soils with a slow natural hydraulic conductivity (e.g., in many clayey soils), in soils with a low porosity, and in soils with an impervious layer at a shallow depth. Of even greater importance, however, is the diminished permeability of the surface and subsurface horizons due to the soil and crop management under wet conditions. The pedogenetic aspects of puddling and the formation of traffic pans are discussed later (see Chap. 5).

In terms of the moisture profile in flooded rice land, the results of puddling and traffic pan formation are profound. The formation of a less permeable subsurface horizon reduces percolation and makes the ponding of water possible, even on soils that were well-drained and permeable. The speed with which the slowly permeable layers form depends on many factors — original textural profile, clay mineralogy, structure, etc. — but indications are that with wet rice cultivation the surface layer permeability diminishes rapidly, and that aquatic conditions can generally be easily maintained a few years after the paddy is constructed. Nakagawa (1975) reported that upon reclamation of moderately permeable freely drained soils for wet rice cultivation, the percolation rate diminished to 20% of the initial rate in 4 years and stayed at relatively stable levels (about 12 mm/day) afterward. For more permeable soils the time to reach an equilibrium rate (about 20 mm/day) was 6 years.

Actual percolation rates may vary from less than 1 mm/day in perennially marshy areas and slowly permeable soils to several centimeters per day in medium- and light-textured anthraquic soils. Such high percolation losses also occur in most medium-textured, floodplain areas of monsoonal Asia (e.g. the Indo-Gangetic plain) where the groundwater generally remains 3 to 30 m below the soil surface throughout the growing season (De Ridder, 1975). In deeply flooded river basins the hydraulic heads provided by the floodwater (1·4 m) are particularly large, and indirect evidence of the occurrence of appreciable percolation is provided by the presence of flood coatings in the subsoil (Brammer, 1971b). These coatings, believed to have been formed under hydraulic pressure, are best developed in the lowest basins. The coatings are composed of surface-soil material that penetrated the subsoil along cracks and other voids.

The permeability of the puddled layer is greatly increased by drying and cracking. Because the cracking process is largely irreversible, the permeability remains high after reflooding, so a single drought may adversely affect the water economy of the rice field. In terraced fields lateral movement through bunds and embankments may further increase water losses, bur part of the seepage water is utilized in lower fields. Losses in a specific paddy field by lateral seepage and vertical percolation are normally higher in the dry than in the wet season because of generally lower groundwater tables and the presence of more cracks in field bunds (Wickham, 1973). Whereas water losses through percolation and seepage may lead to water shortage and crop failure in shallow-flooded rice lands, moderate percolation is often reported necessary for high yields. Percolation rates in the order of 20 mm/day seem to give optimum results in Japan (Ezaki, 1975) in spite of losses of water and nutrients.

As reported by International Rice Research Institute scientists (IRRI, 1975, 1976), an important factor regarding water availability for rice in bunded and leveled fields on sloping land is the topographical position (bund position) in the landscape. Given a similar rate of percolation, the paddy fields on lower slopes will receive and retain more surface water than the higher ones partly because of overflow and partly because of interflow from the higher to the lower paddy fields. To feed the lower paddies, farmers often use early rainwater that has accumulated in the higher paddies but is not sufficient to start the growing cycle. The lower paddies are planted and prepared earlier and may give two consecutive rice crops. This effect, studied in Iloilo and Pangasinan provinces, Philippines, is further enhanced by the often lower permeabilities of the soils at the lower ends of the toposequence and the closer proximity of the groundwater in the lower fields. In many parts of the rainfed rice areas of northeastern Thailand, for instance, the higher members of the toposequence are more sandy and permeable, while percolation from the lower, more clayey members is distinctly lower.

FLOODING REGIMES

A parameter of importance for the distinction of different types of rice land that are subject to natural and artificial flooding is the nature of flooding. Three elements appear to be of major importance here:

- duration and depth of flooding during the period that rice is being grown,
- regularity of flooding as determined by climate and regime of streams and rivers, and

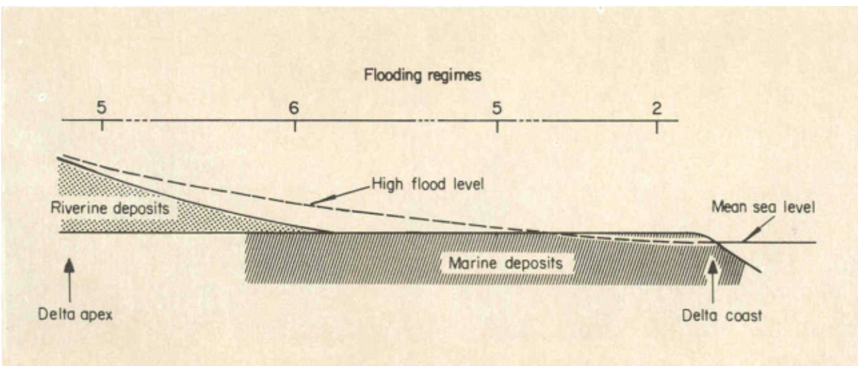
- degree to which flooding is controlled by irrigation, flood protection, and drainage.

Considering rice lands in the light of these elements, it becomes clear that a wide range of flooding conditions can exist. Variations occur in function of site-specific water characteristics. Moreover, the flooding pattern on a given rice land varies considerably from season to season, or within a single season. The following kinds of flooding regimes are a rough guide of what is observed in the field, but we emphasize that shifts between regimes may occur in a given field during the year.

- *Regime 1.* Shallow, irregular, and brief flooding characterizes regime 1. The regime is predominant in pluvial-anthraquic rice fields (rainfed paddies) especially in monsoonal climates where there are irregular periods of drought during the growing season. Rainwater is retained but the duration of flooding is limited to periods of high rainfall. Such rice lands are transitional to dryland conditions. Crop yields are generally low, due mainly to recurrent drought, and crops may fail completely in dry years (Fig. 6). Rice cultivation with this flooding regime is often marginal.

6. Drought causes deep cracking of a puddled soil and may wipe out a rice crop on pluvial-anthraquic rice land. This rainfed paddy scene typifies flooding regime 1.

- *Regime 2.* Shallow, irregular and prolonged flooding characterizes regime 2. The regime is common in both pluvial-anthraquic and in phreatic-anthraquic rice lands in areas of higher rainfall. Rainwater is ponded and stays on the land for longer periods although drought does occur in some years. In addition to rainwater, fields often receive water by overflow from higher fields during and after heavy rainfalls. Hence, the lower paddy fields in a toposequence usually have a better provision of water than the higher ones. Even in areas with sufficient rainfall during the growing season, some paddy fields do not hold water long because of high soil permeability. Such fields, which are usually confined mainly to the higher parts of toposequences, are transitional to regime 1. Regime 2 represents one of the most widespread flooding conditions in monsoonal Asia where irrigation is not applied. It is common in semirecent and somewhat older river and marine terraces that are not subject to natural flooding. Flooding of large areas may occur incidentally during exceptionally high rainfall or high river discharge, but the surplus water is rapidly carried off through natural drainageways and canals to the lower courses of the rivers or to the sea. Land in this regime occupies large areas in river deltas and on coastal plains, where general area flooding is relieved by rapid evacuation of excess rainwater. Thus, for instance, the marine zones of the Mekong Delta in Vietnam and of the Chao Phraya Delta in Thailand fall under this regime (Fig. 7).
- *Regime 3.* Shallow and continuous uncontrolled flooding characterizes regime 3. The regime is found in small areas of nonirrigated rice lands with a climate of high, regular rainfall, as in the equatorial humid areas of Indonesia, Malaysia, and Sri Lanka. The rice lands under this regime are pluvial-anthraquic and phreatic-anthraquic. The most common situation is that the bunded, leveled, rice field receives its water as rainwater and as overflow from the higher to the lower fields. Frequently, such overflow is well-regulated, and in that case, a situation transitional to regime 4 exists.



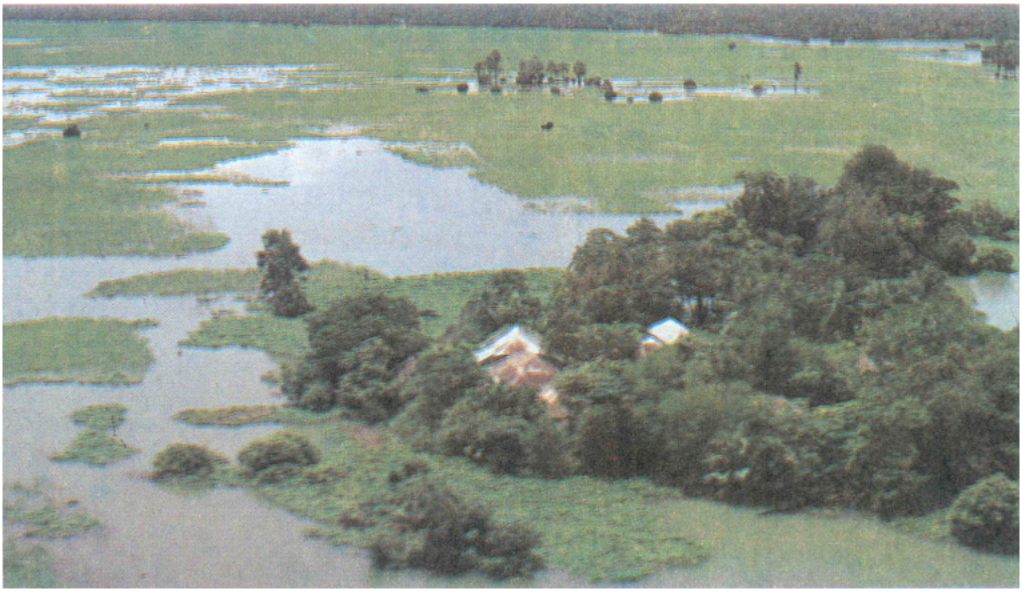
7. Flooding regimes in Southeast Asian deltaic areas (schematic cross section, no scale).

- *Regime 4.* Shallow flooding controlled by irrigation typifies regime 4. All flooded rice lands where at least part of the water is supplied artificially from elsewhere are grouped in this type. Irrigation may be supplemental to rainwater or may be the exclusive water source (e.g. rice fields in arid zones or dry-season rice fields in monsoonal climates). The duration of flooding cannot be specified because it depends largely on water availability and management. Regime 4 is found on all major landscape positions, i.e. in pluvial-anthraquic, phreatic-anthraquic, and fluxial rice lands, although in the latter case, irrigation is confined mainly to dry-season rice. Even though irrigated rice growing has its main extension in broad and flat valleys, plains, and terraces, shallow flooding with irrigation has since time immemorial been applied in other parts of the landscape, i.e. small valleys and terraced slopes where a source of water is available at a higher level. In fact, the use of steep slopes (e.g. in Java, Northern Luzon, Assam) for anthraquic rice culture is strongly enhanced by an ample water supply.

Rice lands that are subject to natural flooding could be subdivided into many subtypes based on depth and duration of flooding. In his description of the rice-growing lowlands of Bangladesh, Brammer (1971b) indicates various flooding patterns that depend on physiographic position of the flooded lands, on the water regime in the major rivers, and on the seasonal pattern of the monsoonal rainfall. This variable pattern can be found in all major, and in most intermediate and minor river plains.

Within the framework of the present typology, a rigorous simplification applies and in this respect it appears relevant to distinguish other kinds of naturally flooded land: where flooding is periodically so deep that only floating rice with ability to elongate can be grown; where the depth of flooding never exceeds the critical level that requires deep-water rice varieties; where rice is grown in the downdraft zones around lakes or in deeply inundated valleys; and where flooding is regulated by tides.

- *Regime 5.* Shallow to moderately deep natural flooding characterizes regime 5. It includes, in their unmanaged form, the low marshy areas where flooding occurs due to rainfall, to rise of the phreatic water above the surface of the land, or to overflow from rivers or streams. Drainage of the water from the land is, however, rapid enough to avoid long periods of flooding to depths of more than 50 cm, and most nonelongating lowland rice varieties can be grown. In West Africa, the term *swamp rice cultivation* is used (WARDA, 1975) for such lands, which are intermittently submerged without artificial water retention. Deep flooding may occur, but it is normally of short duration and occurs mainly as flash floods in narrow inland valleys. In Asia, larger portions of floodplains and many of the central, lower parts of small valleys of creeks and drainageways in are flooding regime 5. Normally, such land is bunded, but in most cases the bunds are low and are often submerged during the growing season. Flooding is intermittent and water does not necessarily cover the land throughout the growing season.



8. Flooding regime 6 is shown in this aerial photograph of a Bangladesh floodplain. (Photo by H. David Cading, Bangladesh Rice Research Institute)

- *Regime 6.* Deep seasonal flooding characterizes regime 6. On lands where deep seasonal flooding occurs, rice varieties that have the ability to rapidly elongate are grown. This permits the plants to grow in water depths of more than 5 m, but water depths are usually from 1 to 2 m. Deep seasonal flooding is most commonly found in the middle reaches of broad river deltas in Southeast Asia (Fig. 8). Here the excess of monsoonal rainwater accumulates in the lower aspects of the landscapes and cannot be evacuated because the flooding coincides with a high level in the rivers. In Bangladesh the deep flooding in the river plains is mainly or totally from accumulating rainwater, and not from overflow of the rivers. Deep seasonal flooding also occurs near the transition between riverine deposits with a distinct though gentle gradient and the much flatter marine deposits as in the Mekong Delta of Vietnam and the Chao Phraya Delta of Thailand (Fig. 7). In other regions, overflow from the rivers to low-elevation backswamps may be the main cause of deep flooding. In the Niger and Senegal River valleys in West Africa, such deep flooding of river backswamps or basins occurs in semiarid zones.

  The rice lands in this flooding regime are neither bunded, nor irrigated. Rice is planted by direct seeding, mainly on dry land, and early growth is without flooding. By the time flooding occurs the rice plants are sufficiently developed and can withstand the gradual rise of floodwater. Elongation may be as much as 12 cmlday, but if the water rises much faster than that, even the deep-water rice varieties may drown.

- *Regime* 7. Shallow flooding after deep seasonal flooding characterizes regime 7. This flooding regime occurs only in special cases, e.g. when rice is grown in bunded fields after a recession of deep floods. An example of regime 7 may be seen around the Ton Le Sap in Cambodia, where the land adjacent to the great lake is deeply flooded by reverse flow from the Mekong River during its peak monsoonal flow. Rice is planted when the level of the lake starts to recede and the planting extends gradually toward the lake's center. The rice lands dry during the growth cycle and unless irrigated, the rice depends on residual soil moisture. Small areas of this flooding regime are found in certain old river channels of the Mae Klong River in the south-eastern part of the Central Plain of Thailand and also in the downdraft zone around artificial water reservoirs.
- *Regime* 8. Flooding to a variable depth, as determined by diurnal or semidinrnal tides, characterizes regime 8. This flooding regime occurs in nonprotected coastal and estuarine zones. Along major tidal creeks it can extend well inland in fiat deltaic areas (Fig. 9). Rice is planted when fresh water supply from the hinterland is sufticient to diminish the salinity of the floodwater to a harmless level. Tidal rice lands are found along many coasts, but because of progressive empoldering, such lands are not extensive in Asia. Relatively extensive areas with flooding regime 8 are found in major estuaries along the west coast of Africa; they are known as mangrove rice lands.

9. Rice in this tidal swamp in Mindanao, Philippines, is subject to variable flooding. Fresh to slightly saline water moves freely in and out of unbunded rice fields depending on the tidal regime.

Variability among regimes

The limits between the various flooding regimes are not rigid, because of the variability in the nature, duration, and depth of submergence. For instance, regimes 1 and 2 are interchangeable in time. Rice lands with no or only limited flooding in normal and dry years may have a regime 2 flooding in an exceptionally wet year. Certain lower aspects of the landscape, such as slight depressions in river terraces, may have moderately deep flooding in some wet years, while normally they would have a regime 2 flooding. In irrigated areas part of the rice fields may revert to regime 1 and 2 in dry years when irrigation water is insufficient. Pluvial-anthraquic rice lands in flooding regime 1 in drier areas, as in northeastern Thailand, may be marginal to such a degree that they are used only in years of an unusually early rainfall.

A single rice field can have two distinct flooding regimes in a given year. The most common combination is found in river plains in pronounced wet-dry monsoonal climates. There, many rice fields with a wet-season regime 5 flooding occur, and are subsequently used in flooding regime 4 (irrigated) in the dry season. In such cases, the rice field should be characterized by both regimes. But no such combined use of regime indication is proposed for the year-by-year variation and each rice field should be characterized according to the dominant flooding patterns for a climatologically average year.

RICE LAND TERMINOLOGY

Table 2 summarizes the main aspects of this chapter and shows how the proposed terms can be used to classify different categories of rice land. Because the natural categories are of little practical value for land with an assured artificial water supply, a fourth category, irrigated rice land, has been added and defined. This purely hydrologic category supersedes the others.

In classifying a given land one should first decide whether it is *irrigated rice land,* i.e. whether the supply of irrigation water is sufficient to meet the requirements of the crop independent of the natural supply in 4 out of 5 years. If it is not, it falls in one of three other categories. Of course some lands qualify for the category *irrigated* only part of the time, e.g. if the irrigation water supply is sufficient for only one crop per year.

The rice lands that do not belong to the irrigated categories are keyed as follows:

- Rice fields situated in the lower aspects of the landscape or in very flat areas, which are flooded partly by water from surface flow or runoff during the greater part of the growing season, are fluxial. In all other cases, the land is either pluvial or phreatic. Whereas in the case of irrigated and fluxial rice lands no general statements can be given on hydrologic conditions in the soil, the difference between pluvial and phreatic rice land depends on internal hydrology.
- In pluvial rice lands, the soil is either well-drained without free groundwater

Table 2. Terminology of rice lands in function of physiography and hydrology.

Intensity of irrigation	Physiographic hydrologic category	Bunding and leveling	Flooding regimes[a]	Terminology proposed	Terminologies replaced				
Zero or low; availability of water depends on natural supply	Pluvial	without	no flooding	Pluvial rice land	Upland			Hill	Dryland
		with	1, 2, (3)	Pluvial-anthraquic rice land	Upland	Lowland		Hill	
	Phreatic	without	no flooding	Phreatic rice land	Upland	Lowland		Hill	
		with	1, 2, 3	Phreatic-anthraquic rice land		Lowland		Hill	
	Fluxial	with or without	2, 3, 5, 6, 7, 8	Fluxial riceland		Lowland	Swamp		
High water is available independent of natural supply in 4 out of 5 years	Irrigated	rarely without	4	irrigated rice land		Lowland			

[a]Regime 1: shallow, irregular, brief flooding; Regime 2: shallow, irregular, prolonged flooding; Regime 3: shallow, continuous, uncontrolled flooding; Regime 4: shallow, continuous flooding controlled by irrigation; Regime 5: shallow to moderately deep seasonal flooding; Regime 6: deep seasonal flooding; Regime 7: moderately deep to shallow flooding after recession of deep floods; Regime 8: tidal flooding.

within the rooting zone of the rice plant, or — as in pluvial anthraquic land — there is a temporary, shallow, perched water table, generally within the 30-cm depth, resting on a traffic pan or, rarely, on an iron-manganese oxide accumulation horizon.

- In phreatic rice land, whether naturally sloping or bunded and leveled (phreatic-anthraquic rice land), free groundwater is present within the rooting zone of the rice plant during most of the growing season. If the groundwater is perched on an impervious layer, this layer should occur below 30-cm depth and is generally not formed by processes associated with wet rice cultivation, i.e. it is not a traffic pan or a thin, strongly indurated accumulation horizon of iron and manganese oxides. To distinguish between pluvial and phreatic categories one generally needs piezometer readings or information on the gley phenomenon in the soil profile. If necessary, the rice land categories can be further specified by indicating the flooding regimes. But it should be realized that because of weather fluctuations, flooding regimes tend to be considerably more variable than the six main categories in Table 2. We hope that the proposed terminology will prove useful and will replace the older terms, which are highly ambiguous.

Recent developments in the establishment of rice land terminology

In recent years a review of existing rice land terminology and the design of a new one have been carried out under the auspices of IRRI. A first approximation of the work by this international committee for terminology and classification was published in 1984 (IRRI, 1984). Apart from a review of 23 existing and widely used systems, this publication contains the proposed IRRI terminology for rice growing environments, based mainly on existing names in use in Asia. Five major categories and a total of 18 subcategories are distinguished. The major categories are:

- irrigated
- rainfed lowland
- deep water
- upland
- tidal wetlands

The division into subcategories is based on temperature regime, flooding regimes, depth of deep water flooding, rainfall pattern and length of growing season, water quality, and soils.

CHAPTER 4

Classification of soils on which rice is grown

RICE GROWS IN A WIDER VARIETY of soils than any other major food crop: soils that range from well drained to poorly drained or waterlogged. The classification of rice-growing soils will, therefore, include most natural soil units or classes that occur in rice-growing areas. But not all natural soil classes are of equal importance for rice growing. First, the preference of rice for conditions where water is freely available will bias the distribution toward hydromorphic soils and also toward soils of high rainfall regions. In the semiarid to arid areas, therefore, only a few natural soil classes are, or can be, used for rice and then only with irrigation. Second, other physical and chemical limitations exclude a number of natural soil classes from rice growing.

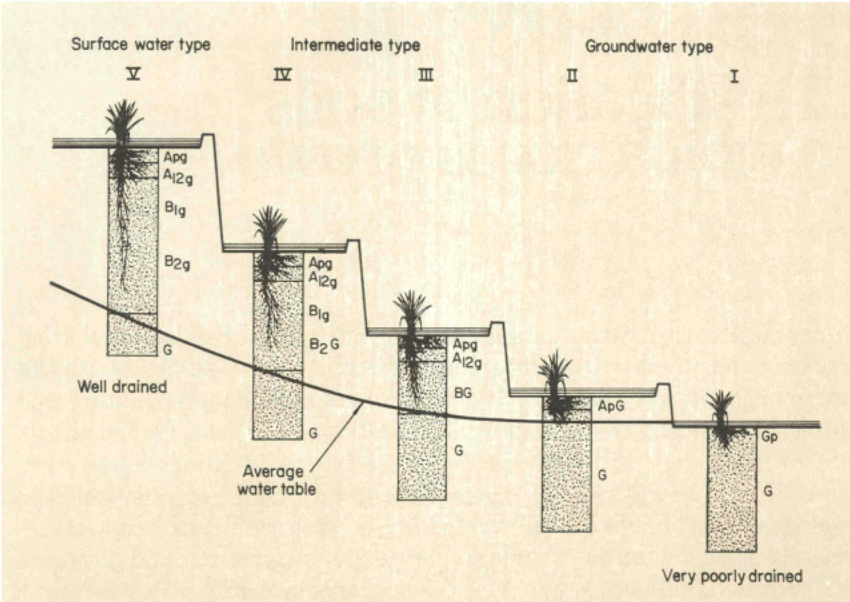
In our opinion soils used for rice growing should be placed in a general soil classification system and should not be treated as an exclusive group. The specific land use of rice in a submerged condition may, however, influence soil properties to such an extent that it becomes necessary to accommodate permanent changes in soil properties in the general classification. This chapter covers the classification, the main distinguishing features, and the distribution of soils on which rice is grown.

CLASSIFICATION SYSTEMS SPECIFIC FOR RICE-GROWING SOILS

Several soil classification systems, both national and international, have been used in rice-growing countries. In most of those systems, no special provision has been made for the classification of submerged rice-growing soils, or paddy soils,[1] unless at a low level of classification (Dudal, 1958; Dudal and Moormann, 1964).

In Japan attempts to develop systems of classification specifically for soils of submerged rice lands started in the 1930's. Several proposals were made, of which Kanno's (1956, 1962) has gained the widest international recognition. The Kanno system uses hydrologic conditions as the main criterion for distinguishing soil classes in the category of *artificial hydromorphous soils* or mineral

[1] The term *paddy soils* is not used in the pedological sense. It connotes the specific type of land use on soils that are submerged during part or all of the growing season, mainly by artificial impounding of water.



1. Catenary sequence of five fundamental families of mineral paddy soils (modified from Kanno, 1956).

paddy soils. The five fundamental soil families of the Kanno system are represented in Figure 1.

Other systems of classification of Japan's paddy soils have been proposed, based on grouping of soil series into 16 classes of paddy soils, e.g. by Matsuzaka (1969) whose publication contains a correlation of those soil series with soil units of the USDA System (USDA, 1960).

Although the approach of Kanno and other Japanese workers has created better understanding of the differences between paddy soils, it has weaknesses when considered within a more generally acceptable system of classification of soils on which rice is grown.

First, no attention is given to soils on which rice is grown without submergence.

Second, the Japanese approach does not cater to conditions usually found in the more freely drained paddy lands where the paddy rice crop is interchangeable with crops grown without submergence.

Finally, morphogenetic changes in paddy soils are not always such that they can be distinguished morphologically from soils with a similar drainage but are not used for rice growing. This is especially true for many poorly drained soils where the changes imposed by the specific use for paddy rice are negligible.

In recent years, the tendency has been to include paddy soils in national or international soil classification systems, but with separate classes provided for soils that, because of the specific land use, have developed new, permanent, diagnostic features. Kyuma and Kawaguchi (1966) review these systems, both for Japan and for other Asian countries.

SOIL TAXONOMY APPLIED TO RICE-GROWING SOILS

The recent soil classification trend in most rice-growing countries is to use *Soil taxonomy* (USDA, 1975) or the legend of the *FAO-Unesco soil map of the world* (UNESCO, 1974) to classify soils at a high level of generalization. In most francophone countries, variants of the French Commission de Pédologie et de Cartographie des Sols (1967) classification system are used for soil classification. Apart from these worldwide soil classification systems, many of the countries in Asia and Africa use national systems that correlate to different degrees with the international systems.

We use *Soil taxonomy* for the classification of rice-growing soils, with the parallel soil units of the FAO-Unesco legend indicated where applicable. *Soil taxonomy* is a sufficiently complete system to classify most of the soils discussed. A major difficulty is that for certain countries, no data on soils are available to permit their placement in the system.

Soil taxonomy is a multicategoric system of soil classification. The units or taxa recognized in a category are subdivided according to precisely defined characteristics in the next lower category. In the highest category, the soil order, 10 units or taxa are recognized, which together cover all known soils of the world. In the lowest category, the soil series, about 10,500 taxa had been recognized and described in the U.S. alone by 1975. The total number of possible soil series in the world is many times that number. If rice is assumed to grow on about 2% of those, a description of all of them is impossible here.

The description of rice-growing soils is, therefore, limited to the highest categories, which implies that only generalized interpretations of the relationship between soil conditions and growth performance of the rice crop can be given. The six categories in *Soil toxonomy* are:

1. ORDERS. The soil orders are separated on the basis of significantly different soil genesis. Rice is grown on all of them:

- *Alfisols:* soils with marks of translocation of silicate clays without excessive depletion of bases and without a mollic epipedon. (See Mollisols.)
- *Aridisols:* soils characterized by lack of available water most of the time, by a surface horizon not significantly darkened by humus, and by the absence of wide cracks.
- *Entisols:* soils in which any major set of soil-forming processes is absent and which do not have distinct pedogenetic horizons.
- *Histosols:* soils characterized by a high organic matter content in the major part of the profile down to 80 cm.

- *Inceptisols:* soils that have available water for more than 3 consecutive months during a warm season and that have one or more pedogenetic horizons other than those used to characterize other orders.
- *Mollisols:* soils that have a dark-colored, well-structured, deep surface horizon (Mollic epipedon) and a high base-saturation throughout.
- *Oxisols:* soils showing extreme weathering of most minerals, absence of translocation of silicate clays, and a low activity of the clay fraction.
- *Spodosols:* soils with marks of translocation and accumulation of humus and aluminum, or humus, aluminum, and iron as amorphous materials.
- *Ultisols:* soils with marks of clay translocation and of intensive leaching, with depletion of bases.
- *Vertisols:* clay soils, with marks of regular mixing of the soil that prevents the development of diagnostic horizons and with pronounced changes in volume with changes in moisture (cracks, slickensides, gilgai microrelief).

2. SUBORDERS. The differentiae used to define taxa at the suborder level vary. In regard to rice-growing soils, the suborders that differentiae wet soils from better drained soils in the same order are most important.

Other suborder criteria that relate to soil genetic properties and to the moisture regime of the soils allow a distinction between soils with very dry (xeric, torric), seasonally dry (ustic), and continuously moist (udic, perudic) moisture regimes.

3. GREAT GROUPS. Soils placed together as a single great group have:

- close similarities in kind, arrangement, and degree of expression of soil horizons;
- close similarities in soil moisture and temperature regimes; and
- similarities in base status.

4. SUBGROUPS. There are three kinds of subgroups — subgroups representing the central concept (typic); subgroups that are transitional to other orders, suborders, or great groups (intergrades); and subgroups that have one or more other aberrant properties (extragrades). The latter are important in the classification of paddy soils that have acquired aberrant new properties because of the specific water regime in flooded rice lands.

5. FAMILIES. Soils in one family have similar physical and chemical properties that affect their responses to management. Particle-size distribution, mineralogy, and temperature regime are the most important criteria in use at the family level. This category of the system is strongly related to the quality of soils for a specific land use. Soils belonging to the same family should have a similar quality for rice growing and require similar management practices to maximize yields.

It is impracticable to deal with even a fraction of the soil families to which rice soils belong, but we pay special attention to particle-size distribution (texture) and mineralogy in Chapter 6.

6. SERIES. The series is the lowest category in the system. It groups soils that have almost the same characteristics, which are not readily altered. Thus, nutrient status of the surface horizon is not commonly a criterion for separating two soils in a series, but the changes imposed by the use of the land as a paddy field are frequently permanent enough to serve as criteria to distinguish specific series for that type of land use.

The nomenclature used in *Soil taxonomy,* confusing on first sight, is systematic and easy to understand once the principles are known. The formative elements of each soil name, up to the subgroup level, are derived mainly from Greek or Latin. The elements are usually connotative of some important characteristic of the soils they classify. For example:

Order:	Ultisol —	*Ult* connotes the ultimate, i.e. soil formation and leaching have greatly progressed; *sol* means soil and is the common ending of all orders.
Suborder:	Aquult —	*Aqu* as in aqua (water) connotes a moisture regime determined by high groundwater; *ult* is taken from the order name.
Great group:	Tropaquult —	*Trop,* as in tropical, connotes a humid and continuous warm climate; aquult is taken from the suborder name.
Subgroup:	Typic Tropaquult —	*Typic,* as in typical, connotes the central concept of the great group.

The formative elements in the names of soil orders, suborders, and great groups are given in Tables 1 to 3. Only the formative elements used in this chapter are mentioned.

As stated in the introduction of *Soil taxonomy,* considerable gaps exist in the classification of soils in the intertropical areas, and, thus no proposals are developed for classifying soils altered by flooding for rice or taro. We discuss the taxa of importance for rice growing in the order in which they appear in *Soil taxonomy.* The classification at the third and fourth level, i.e. great groups and subgroups, is discussed only for the main rice-growing soils.

For quick reference, the orders are listed in Table 4 according to their importance for rice growing. Within each order, the relative importance of various suborders is given and the most common types of rice land are indicated.

Classification into the *minor importance* category is either because such suborders are marginally suited for rice and hence not extensively in use for the crop or because the distribution of the suborder is limited. Soils that are suited for rice cultivation but have a limited distribution include, for instance,

Table 1. Formative elements in names of soil orders.

Name of order	Formative element in name of order	Derivation of formative element
Alfisol	Alf	Meaningless syllable
Aridisol	Id	L. *aridus,* dry
Entisol	Ent	Meaningless syllable
Histosol	Ist	Gr. *histos,* tlssue
Inceptisol	Ept	L. *Inceptum,* beginning
Mollisol	Oll	L. *mollis,* soft
Oxisol	Ox	F *oxide,* oxide
Spodosol	Od	Gr. *spodos,* wood ash
Ultisol	Ult	L *ultimus,* last
Vertisol	Ert	L *verto,* turn

Source: Soil taxonomy (USDA. 1975)

Table 2. Formative elements in names of suborders.

Formative element	Derivation	Connotation
And	Modified from ando	Andolike
Aqu	L. aqua, water	Aquic moisture regime
Arg	Modified from argillic horizon; L. *argilla,* white clay	Presence of argillic horizon
Fluv	L. *fluvius,* river	Floodplain
Hum	L. *humus,* earth	Presence of organic matter
Ochr	Gr. base of ochros, pale	Presence of ochric epipedon
Orth	Gr. *orthos,* true	The common ones
Psamm	Gr. *psammos,* sand	Sand texture
Rend	Modified from Rendzina	High carbonate content
Ud	L *udus,* humid	Udic moisture regime
Umbr	L. *umbra,* shade	Presence of umbric epipedon
Ust	L. *ustus.* burnt	Ustic moisture regime
Xer	Gr. *xeros,* dry	Xeric moisture regime

Source: *Soil taxonomy* (USDA, 1975).

Andepts and (tropical) Udolls. The local importance category is for soils in major rice-growing areas not used, or rarely used, for rice growing outside of such zones.

The legend of the *FAO/Unesco soil map of the world* defines soil units at two levels of generalization. Because similar diagnostic criteria are used for the definition of most soil units or taxa in both *Soil taxonomy* and the FAO/Unesco systems a fairly complete correlation is possible. We list corresponding FAO/Unesco names in parentheses to enable readers to refer to the soil map of the world[2]. Those maps were extensively used in the preparation of this chap-

[2]Available from Unesco, Place de Fontenoy, 75700 Paris, France.

Table 3. Formative elements in names of great groups.

Formative element	Derivation	Connotation
Alb	L. *albus,* white	An albic horizon
And	Modified from ando	Andolike
Arg	Modified from argillic horizon; L. *argilla,* white clay	An argillic horizon
Chrom	Gr. *chroma,* color	High chroma
Dystr, dys	Modified from Gr. *dys,* ill; dystrophic, Infertile	Low base saturation
Eutr, eu	Modified from Gr. *eu,* good; eutrophic, fertile.	High base saturation
Fluv	L. *fluvus,* river	Floodplain
Frag	Modified from L. *fragllis* brittle	Presence of fragipan
Hal	Gr. *hals,* salt	Salty
HapL	Gr. *haplous,* simple	Minimum horizon
Hum	L. humus, earth	Presence of humus
Natr	Modified from *natrium,* sodium	Presence of natric horizon
Ochr	Gr. base of *ochros,* pale	Presence of ochric epipedon
Pale	Gr. *paleos,* old	Excessive development
Plint	Gr *plinthos,* brick	Presence of plinthite
Psamm	Gr *psammos,* sand	Sand texture
Quartz	Ger *quarz.* quartz	High quartz content
Rhod	Gr base of *rhodon,* rose	Dark-red color
Sal	L base of sal, salt	Presence of salic horizon
Sulf	L sulfur, sulfur	Presence of sulfides or their oxidation products
Torr	L. *torridus,* hot and dry	Torric moisture regime
Trop	Modified from Gr *tropikos,* of the solstice	Humid and continually warm
Ud	L *udus,* humid	Udic moisture regime
Umbr	L base of *umbra,* shade	Presence of umbric eplpedon
Ust	L base of *ustus,* burnt	Ustic moisture regime
Xer	Gr *xeros,* dry	A xeric molsture regime

Source: *Soil taxonomy* (USDA 1975).

ter. If a significant part of FAO-Unesco soil unit is not included in the Soil taxonomy taxon, the name of the soil unit is followed by *pt.,* as an abbreviation of part.

Additional information on the classification of rice-growing soils, most specifically of soils subjected to various flooding regimes, is in the proceedings of a 1977 IRRI symposium on soils and rice (IRRI, 1978).

Alfisols (Luvisols, Eutric Nitosols)

The soils in this order show marks of clay translocation, resulting in clay accumulation (argillic horizon) at different depths in the profiles. Leaching of

Table 4. Major rice-growing soil taxa and dominant types of rice lands.

Order	Suborders in use for rice growing		
	Major Importance	local Importance	Minor Importance
Inceptisols	Aquepts ph, f, i	–	Andepts p, i
	Ochrepts[b] p, ph, i		
	Tropepts[b] p, ph, i		
Alflsols	Aqualfs ph, f, i	Udalfs p ph, i	
	Ustalfs[b] p, ph, i		Xeralfs i
Ultisok	Aquults ph, f, i	Humults p, i	Ustults[a], ph, i
	Udults p, ph, i		
Entisols	Aquents ph, f	Fluvents ph, i	Ortnents ph
			Psamments ph, i
Vertisols	–	Uderts ph, f i	Torrerts i
		Usterts f, i	Xererts i
Mollisols	–	Aquolls f, i	Udolls p, ph. i
Oxisols	–		Ustox p
			Ortnox p
Aridisols	–	_	Orthids i
Histosols	–	–	Hemists ph, f
			Saprists ph, f
Spodosols	–	–	Aquoas ph, f

[a]Categories of rice land p = pluvial and pluvial anthraquic; ph = phreatic and phreatic anthraquic; f = fluxial; i = irrigated. [b]Aquic subgroups mainly.

bases is not excessive, and so base saturation is medium to high in the argillic horizon. Soils belonging to this order do not have a thick dark-colored. highly saturated, and well-structured surface horizon (a *mollic epipedon).*

Alfisols occur throughout the area where rice is grown but they are most common in the drier portions of that area, notably in zones with apronounced dry season (ustic moisture regime). In the wetter, intertropical areas (udic moisture regime) Alfisols are found where the parent material is more basic, or on young formations. or both, i.e. bases have not been leached to a degree that excludes those soils from the Alfisol order.

The following suborders are found among Alfisols on which rice is grown.

AQUALFS (Gleyic Luvisols). The Aqualfs are Alfisols that are water saturated for a considerable part of the year unless artificially drained. These soils generally occupy lower parts of the landscape, such as lower basins in river alluvial terraces, slightly elevated coastal terraces, and the poorly drained sites in undulating areas that are dominated by more freely drained Alfisols and Ultisols. Large consolidated surfaces of Aqualfs are found on semirecent river terrace formations of the major rivers of Southeast Asia.

Almost all Aqualfs in Asia are used for bunded and leveled paddy fields. In West Africa the growing of rice on Aqualfs is increasing, although without the Asian type of water control. The Aqualfs in West Africa are restricted to swales and foot slopes in the moderately dry to dry savanna areas. Except for the most sandy families, Aqualfs have a moderate to high potential for rice.

The following are among the great groups of Alfisols used for rice growing:

- *Tropaqualfs:* characterized by a warm climate without any significant fluctuation of soil temperature. They occur in an area roughly south of the 17th parallel in Asia and Africa; their southern boundary is not known.
- *Ochraqualfs:* with a more pronounced seasonal variation in soil temperature (more than 5°C difference between summer and winter temperature at a 50-cm depth). Their most common occurrence is in northern India north of Hyderabad, and in parts of Burma, northern Vietnam, and eastern China. Part of Japan's paddy soils, classified as *Gley upland soils,* are Ochraqualfs (Matsuzaka, 1969).
- *Albaqualfs* (Eutric Planosol. *pt.*): with an abrupt textural change from the surface horizons to the argillic horizon, and often with a bleached (albic) horizon below the plow layer. These are important rice-growing soils in the southern United States, but are of only local importance elsewhere.

Of the other Aqualf great groups, Natraqualfs (Gleyic Solonetz *pt.*) should be mentioned. These soils have a high sodium content in the subsoil and pose problems for rice cultivation unless both irrigation with good quality water and drainage are assured. The Natraqualfs occur in small patches in the drier (ustic) parts of the rice-growing areas.

USTALFS (Luvisols, except Gleyic, pt.; Eutric Nitosols *pt.*). The prefix *ust* connotes a climate in which the nonirrigated soils is too dry for most annual crops for a period of at least 3 months of the year, but where there is enough soil moisture for plant growth during at least 6 months.

Ustalfs are widespread in the tropical and subtropical areas with a pronounced seasonal rainfall. They are dominant upland soils in southeast India and in the dry zone of Sri Lanka, but they occur on only small surfaces in Southeast Asia. In Africa, the Ustalfs dominate in the savanna and dry forest zones where annual rainfall is between 600 mm and 1,500 mm. On well-drained upland Ustalfs, rice is grown in systems of shifting cultivation. Preference is given to deeper, medium- to fine-textured Ustalfs with a good water-holding capacity. A requirement for the use of such Ustalfs for dryland rice is sufficient and regular rainfall.

In Asia, considerable areas of the flat to gently undulating Ustalfs, often found on river terraces and peneplains, are in use as rice land. Such land is mostly of the pluvial-anthraquic or phreatic-anthraquic type but is also irrigated where irrigation water is available. These rice lands are found in the lower aspects of the landscape, and most of the rice-growing Ustalfs are transitional to the Aqualf suborder, This is expressed in the subgroup level (aquic subgroup).

Use of the aquic subgroups of the Ustalfs for rice is increasing in West Africa, but water control there as practiced in Asia is rare. The large areas of well-drained upland Ustalfs in West Africa and in parts of East Africa cannot be used for sustained rice cultivation without irrigation because the wet-season rainfall pattern is highly irregular. Even in the pluvial anthraquic rice fields on Ustalfs in Asia, crop failures occur and the average rice yields are lower than those on the associated hydromorphic soils.

Among the great groups of Ustalfs, the following are used for various forms of rice cultivation.

- *Paleustalfs:* thick reddish to brownish Ustalfs on stable landforms that are flat to gently undulating. They are common in the rice-growing Ustalf areas on river terraces in Asia. In West Africa, southeastern India, and the dry zone of Sri Lanka, large surfaces of Paleustalfs are found on old peneplains over crystalline rocks. Although Paleustalfs form an important group in the intertropical areas, their use for rice growing is only limited. Most are only marginally suited for dryland rice without any form of water management. The Paleustalfs are extensively used for rice on phreatic-anthraquic lands in flat or slightly depressed sites, but the suitability for this type of rice-growing varies considerably within the group. Soils belonging to the aquic subgroups are best. Moreover, the quality of such paddy land increases for soils with a finer, more clayey texture in the subsurface layers. In such soils vertical water movement is slowed, especially if puddling results in a plow pan. Where irrigation is available, clayey Paleustalfs produce excellent rice crops.
- *Haplustalfs:* relatively thin Ustalfs. They are not widespread among the Ustalfs in the intertropical rice-growing areas but are of local importance outside of that zone. Rice grown on Haplustalfs follows the pattern discussed for Paleustalfs.
- *Rhodustalfs:* dark-red Ustalfs, developed mainly from basic parent materials with a high content of iron and manganese. Rhodustalfs are rare in the main rice-growing areas, but are common in pluvial rice land in hilly areas with an ustic soil moisture regime. Dryland rice is also grown on the closely related Rhodic subgroup of the Paleustalfs, which have deeper profiles than the Rhodustalfs.
- *Natrustalfs* (Solonetz, *pt*): Ustalfs with a high sodium content in the subsoil. Some of them are used for rice if good quality irrigation water is available, but most are problem soils with marginal yields.

UDALFS (Luvisols, except Gleyic, *pt.,* Eutric Nitosols, *pt.*). The prefix *ud* connotes a climate in which the nonirrigated soil profile is not dry in any part below the surface horizon for as long as 90 days a year.

The world’s area of rice-growing Udalfs is believed to be small, although they may be of local importance as rice-growing soils in parts of China. Few data from China are available, but Udalfs are reported in Korea (Yong Hwa Shin, 1978). In the western part of the coastal rice-growing area of Texas, USA, Udalfs are reported highly productive for irrigated rice (Westfall, 1975).

In the udic intertropical areas, some rice-growing Udalfs are found on relatively young river terraces and on basic rocks in hilly positions. On the young river terraces, rice is grown mainly in phreatic-anthraquic fields, while in the soils on basic rocks, rice is grown in a shifting cultivation pattern.

Aridisols (Yermosols, Xerosols, *pt.)*

As the name Aridisol indicates, these are soils of arid areas. Unless irrigated, moisture is not continuously available for more than 3 months. Aridisols are weakly developed. In the rice-growing zones they are often saline, or may become saline with careless irrigation water management.

Irrigated Aridisols on which rice is grown are mainly found in the lower Indus basin in flat areas of alluvial origin. Interpretation of the *FAO-Unesco soil map of the world* indicates that most of the soils in that area are actually, or potentially, saline, with considerable areas of Aridisols and Entisols (see Entisols below) that are saline at shallow depth or at the surface. Salinization is a main problem, but the use of land for irrigated rice may offset the destructive effect of salinization in irrigated Aridisols. Recent expansion of irrigated rice growing in the Indus basin is related to this.

Some irrigated rice is grown locally on Aridisols in the Senegal River basin of West Africa. However, only a fraction of the world's extensive areas of Aridisols is irrigated and, except where good quality irrigation water is relatively plentiful, no rice is grown.

Entisols (Fluvisols, *pt.,* Gleysols, *pt.,* Arenosols, *pt.,* Regosols, *pt.)*

The common characteristics of Entisols is that they are soils in which no profile, or only a weak profile, has developed. At most, only a thin A horizon has formed.

The reasons for the absence of clear genetic horizons are diverse. The parent material may be inert, as in the case of quartz sand, or the time of formation may have been too short, as in actively eroding landscapes or in lands where new material is added faster than a soil profile can develop, e.g. in floodplains where material is deposited annually. Continuous saturation with water, as in mangrove swamps, may also inhibit horizon formation. Man-made Entisols occur on rice terraces such as the famous Banaue terraces of the Philippines, where the soil profile is created by bringing soil materials from elsewhere.

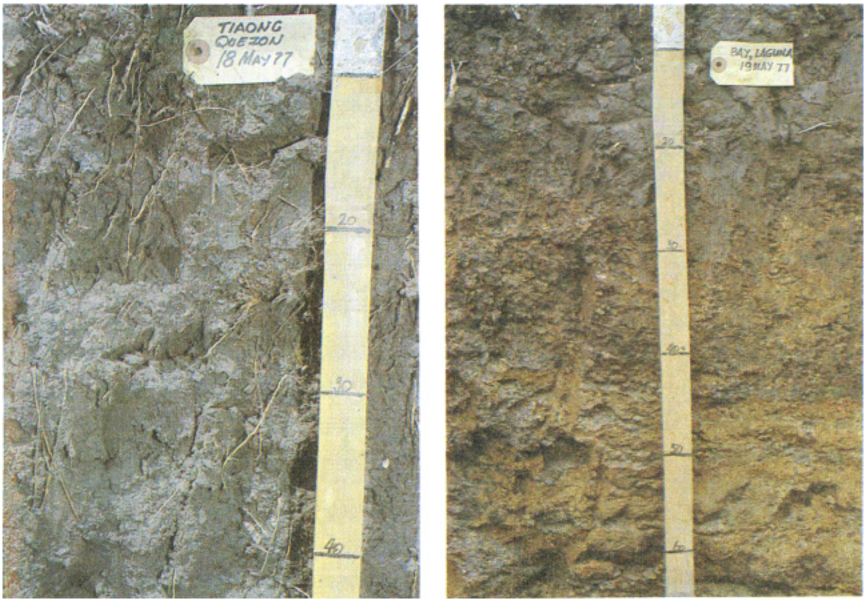
Profile development in most rice-growing soils has gone beyond the Entisol stage. This is particularly so for the wide expanses of wetland soils in alluvial plains, where aggradation is so slow that horizons have formed in addition to the weak A horizon admitted for Entisols.

Rapid changes take place in many soils on active floodplains. Brammer (1971b) indicates that on the aggrading floodplains some Entisols may develop into Inceptisols in a few decades.

Rice-growing Entisols occur in all areas and in most topographical positions of the rice-growing zone of the world, but there are no large consolidated areas except in wetlands.

The following suborders are used for growing rice.

AQUENTS (Gleysols, *pt.;* Fluvisols, *pt.*). The Aquents are the wet Entisols in tidal marshes, on the margins of lakes where the soil is continuously saturated with water, in periodically watersaturated floodplains, and in foot slope areas that are continually wet through interflow water (Fig. 2). The strong gley soils in Japan are Aquents. Aquents are reported on large surfaces in the floodplains of the Ganges-Brahmaputra river system (Brammer, 1971b; Murthy, 1978) although such soils may have to be at least partly reclassified as Inceptisols. Indeed, in most larger floodplains in Southeast Asia, all but the youngest floodplain and marine soils are altered too much to permit classification as Aquents.



2. Two contrasting soils of wet-cultivated rice land, developed in volcanic deposits in southern Luzon, Philippines. On the left is a Typic Hydraquent [fine, montmorillonitic (calcareous), isohyperthermic] showing dgray, unmottled matrix throughout. Perennial upwelllngofwaterfrom higher areas prevents periodic oxidation and mottling with iron oxides, and causes a low bulk density and low bearing capacity. Low availability of zinc induced by excessive wetness causes severe zinc deficiency in rice in this otherwise fertile soil. The roots in the soil are from weeds during a fallow. To the right is a Vertic Tropaquept (fine, montmorillonitic, non-acid, shallow) showing a periodically reduced, gray surface soil over a predominantly oxidized brown mottled B horizon. Soils such as this have yielded up to 11 t/ha under optimal management at the International Rice Research Institute.

Rice in Asia is grown on most Aquents, the hydrological requirement being that the surface layers dry periodically to a sufficient degree so that oxidation can take place. The critical depth of drying is not exactly known, but indications are that about 10 cm is sufficient.

The general conditions of rice growing on Aquents are usually far from optimum. Salinity and potential acidity are problems on Aquents in the coastal fringes, zinc deficiency or iron toxicity occurs in Aquents in inland areas, and rice suffocation and damage due to recurrent deep flooding are not rare on the river plains. It is amazing, however, that by elaborate land and water management and by proper timing of the crop, Asian farmers tenaciously use such problem soils for rice.

An example of Aquents use for rice is on the coastal areas of Kerala state, India. There, shallow coastal lakes are bunded; the lower part of the bund is permanent, while the upper part is reconstructed each year after high floods. The polders thus formed (from 100 to 650 ha) are pumped out when the coastal lake water is nonsaline because influx of fresh river water is sufficient. Rice is planted on the lake-bottom soil, which is an Aquent of variable but mostly medium texture. Most of the land reverts to lake when high floods occur later in the rainy season.

A less elaborate variant can be seen in the lower reaches of some of the rivers in Senegal (Casamance) and Gambia. There, saline and potentially acid mangrove swamps are cleared and rice is direct seeded during the rainy season when the land is flooded with fresh river water. The salinity level then diminishes to a level that is no longer harmful to rice. In dry years, such as the early 1970's, the river floods fail and so does the rice crop, because of salinity.

In many coastal areas, especially where tides are not pronounced and where little damage from typhoonal floods is expected, the accruing land in deltas is rapidly secured, desalinized, and used to grow rice. Such soils are Aquents, usually with a clayey texture, but their evolution is toward Inceptisols, a stage that they reach in a relatively short time — probably less than 100 years.

Outside the coastal areas, the Aquents on which rice is grown are limited mainly to poorly drained backswamps on river plains and to narrow, continuously wet valley bottoms in high-rainfall zones. A high proportion of the soils in the Banaue rice terraces of the Philippines are man-made Aquents.

Great groups of the Aquents used for rice growing in varying degrees include:

- *Sulfaquents:* soils with sulfidic materials within 50 cm of the surface, which are potentially acid.
- *Fluvaquents:* wet soils of floodplains and coastal areas,
- *Tropaquents:* wet soils, other than the above, of the tropical areas in which the soil temperature fluctuates less than 5°C between the warmest and coldest months,
- *Psammaquents:* sandy-wet Aquents, exclusively of sandy Tropaquents,
- *Haplaquents:* wet Aquents mostly in depressions, and with a soil tempera-

ture of more than 5°C between warmest and coldest months; and

- *Hydraquents:* very wet Aquents, permanently saturated with water and with a low bulk density and low bearing capacity.

PSAMMENTS (Regosols, *pt.;* Arenosols, *pt.*). The Psamments are Entisols that are sandy to a 1-m depth, unless they overlay consolidated rock or laterite. Groundwater is always deeper than 50 cm and usually much deeper, which excludes these soils from the Aquents. Sandy soils on raised beaches and others in river terraces are Psamments in the general zone where rice is grown.

Little rice is grown in Psamments, and yields are distinctly marginal wherever such soils are used for rice. In all cases, only the aquic subgroups are used, i.e. soils that show signs of wetness at medium depth. Pluvial anthraquic rice land on Psamments occurs on sandy terrace deposits, e.g. in northeastern Thailand.

FLUVENTS (Fluvisols, *pt.*). The Fluvents are brownish to reddish soils in recent water-deposited sediments, and are usually less than a few hundred years old in the main rice-growing areas. They are flooded frequently unless protected by dikes and new material is regularly deposited leading to stratified profiles and an irregular decrease of the organic matter content with depth.

Fluvents are often found adjacent to streams on alluvial fans, and more seldom in coastal delta areas. If no new sediments are deposited regularly, e.g. when rivers change their course, such soils rapidly form horizons that exclude them from the Entisols. Thus, on old river levees, as in the Mekong River delta and the central plain of Thailand, and in deltaic areas along the southeast coast of India, soils of some age are found that are no longer Entisols but that have evolved toward Inceptisols and, more rarely, to Alfisols (Haplustalfs in Thailand and India).

Areas of rice-growing Fluvents occur outside of the continuously warm climate where the evolution from Entisols toward Inceptisols would be slower. In Japan, some of the yellowish-brown wetland soils on slightly high sites on alluvial plains are classified as Fluvents (Matsuzaka, 1969). Others are reported from Korea (Yong Hwa Shin, 1978) and Europe (Matsuo et al., 1978).

Where they grow rice, most nonsandy Fluvents are productive; with irrigation they are highly productive. Moreover, many of the medium- to fine-textured Fluvents are well suited for multiple cropping. In the central plain of Luzon, both field crops and vegetable crops are extensively grown in rice-based cropping systems on medium- to fine-textured Fluvents.

Great groups of the Fluvents of some importance for rice growing are described below:

- *Xerofluvents and Torrifluvents:* soils of dry areas on which rice can grow only with irrigation. The Xerofluvents are found in a Mediterranean type of climate; some rice-growing soils in Spain belong to this great group. Torrifluvents grown to rice are found in the drier parts of the Indus valley and in Egypt's Nile River valley.

- *Ustifluvents:* most of the Fluvents in the monsoonal climates with a pronounced dry season. Rice is grown in the rainy season, but when irrigation is available more than one crop of rice can be grown. These soils are commonly used for other crops.
- *Tropofluvents:* the Fluvents of the continuously moist warm climates, where the difference in soil temperature between the coldest and warmest months is less than 5°C. Such soils are not extensive and are partially used for rice, which is grown mainly in phreatic-anthraquic or irrigated rice fields.
- *Udifluvents:* Fluvents of continuously moist climates where differences in soil temperature between the coldest and the warmest months are more than 5°C.

Histosols (Histosols)

The Histosols are soils dominantly composed of organic matter, and are commonly known as peat or muck. By definition more than half of the upper 80 cm should be organic soil material. Organic soil material has 18% or more organic carbon if the mineral fraction is 60% or more clay, and 12% more organic carbon if the mineral fraction contains no clay. The definition and the classification of Histosols are considered provisional.

The major areas of Histosols in the world's rice-growing zone occur in the high-rainfall equatorial part of Southeast Asia — East and West Malaysia, the islands of Sumatra and Kalimantan, and West Irian in Indonesia. Histosols are found to a lesser extent in the Mekong Delta of Vietnam and in the Ganges Delta. Elsewhere, Histosols are confined mainly to small inland swamps.

The Histosols of Southeast Asia are found largely in coastal areas, protected from direct intrusion of the sea by beach ridges. Sedimentation of mineral soil material is minimal. These coastal peat formations have a marked relief with a domed high portion in which the peat-forming vegetation (mainly forest) *grew in itself,* and with lower transitions toward mineral soils (Aquents) close to the rivers and the sea. The domed portions are purk organic matter with a low bulk density.

Rice is grown on the thinner, more mineral Histosols, but because of physical or chemical problems neither the surfaces planted to rice nor the rice yields are important (Fig. 3). The few rice-growing Histosols are mainly in the suborder Hemists, in which most of the plant remains have decomposed, and in which groundwater is at, or close to, the surface unless drainage has been applied. The suborder includes potential and actual acid sulphate soils that are dominantly organic, and respectively classified as Sulfihemists and Sulfohemists.

3. Mineral disorders and low bearing capacity are important limitations to the use of Histosols for wetland rice. In this Laguna, Philippines, rice field, land preparation consists only of turning the weeds by hand. Weeding is practically impossible for several months after transplanting because rice plants become dislodged when anyone enters the field.

Inceptisols (Gleysols, *pt.,* Andosols, Cambisols)

The Inceptisols are immature soils with weakly developed profile features. There are diverse reasons for the Inceptisols' weak profile development and lack of genetic horizons and diagnostic characteristics that are determinants for the more developed orders. Inceptisols are found in a wide range of environments — excluding only the aridic moisture regime of the deserts — on diverse parent materials, and in virtually the whole range of landscape positions.

Inceptisols form the most important single soil order among the rice-growing soils. In the rice-growing zone, many of soils that were grouped in the category of Alluvial Soils in former classification systems are Inceptisols. Although formed on relatively recent alluvial deposits, they have undergone a definite, although restricted, genetic profile development. Thus, the major rice-growing alluvial plains — both river floodplains and deltaic areas — are to a large extent Inceptisols.

Outside of the major and minor plains, Inceptisols are of local importance in rice growing. They are found on the younger marine and river terraces, and also on undulating to rolling uplands where the soil is rejuvenated due to erosion or deposition, e.g. in some volcanic areas where regular ash deposits counteract the advancement of soil-forming processes.

The suborders of Inceptisols of importance for rice growing are described below.

AQUEPTS (Gleysols, *pt.;* Thionic Fluvisols, *pt.*). The Aquepts include all of the Inceptisols that are water saturated for at least part of the year and show either a high sodium content in the first 50 cm, or the gray and rusty mottling characteristic for periodic wetness, or both. They are distinguishable from the Aquents by a subsurface horizon that has changed sufficiently in color and structure to be called a B horizon (Fig. 2). This type of horizon is called a cambic horizon. Also included in the suborder are soils with a sulfuric horizon at less than 50 cm (acid sulfate soils) and soils with a thick, A horizon that has a high humus content.

Aquepts are a main component of the rice-growing river and deltaic plains and are used extensively for rice growing on all the major alluvial plains of Asia, except those in climates with an aridic soil moisture regime. Scattered small areas of Aquepts occur in many swales, and small valleys scattered through most upland areas of the rice-growing zone. In Asia, most of such Aquepts are terraced and used for rainfed or irrigated rice.

Aquepts of various kinds occupy the greater part of the lower Ganges-Brahmaputra floodplain and delta (Brammer, 1971b), and are also locally important in the low alluvial terraces of those rivers. The same pattern is found in other Asian floodplains. In Japan, many of the paddy soils are Aquepts. They belong to ando lowland soils, ando gley soils, aquic grayish-brown upland soils, gray lowland soils, grayish-brown lowland soils, grayed gley soils, and upland gley soils in Matsuzaka's classification (1969). In Europe and in the southern United States, irrigated Aquepts are important for rice.

On other continents, Aquepts on river plains and deltas show an important potential for rice growing (e.g. Africa's Niger River delta). But most are underutilized because of the lack of adequate soil and water management technology. In West Africa, increasing use is made of such soils for rice but water control is rare. Part of the so-called swamp rice of West Africa is grown on Aquepts. However, when there is no standing surface water, the rice on Aquepts is locally classified as upland; rice in reclaimed coastal mangrove land with Aquepts is called *mangrove swamp* rice.

It is difficult to give a general evaluation of the quality of Aquepts for rice. They commonly have sufficient water for at least one annual rice crop. Within this context, however, the soil quality varies from highly productive to marginal. Although many of the best rice lands are on clayey, mineralogically rich Aquepts, other Aquepts pose problems that include high permeability as in sandy Aquepts, low inherent fertility as on soils with a kaolinitic clay mineralogy, soil acidity as in acid sulfate soils, salinity, alkalinity, deep floodwater, and flash floods. Many of these production-determining parameters are incorporated in the lower categorical levels of *Soil taxonomy,* especially in the family levels.

The most important great groups of the Aquept suborder include:

- *Sulfaquepts* (Thionic Fluvisols, *pt*): The Sulfaquepts are acid sulfate soils that became strongly acid at less than 50-cm depth after drainage and aeration. Such soils show the characteristic straw-yellow mottles of basic iron sulfate (jarosite) below, and sometimes even in the A horizon. Most Sulfaquepts have thick surface horizons with high humus content; quite a few may show thin layers of organic materials at the surface.

  Most Sulfaquepts are problem soils for rice and the effects of their acidity is dealt with in Chapter 6. However, not all Sulfaquepts are continuously toxic. Avoiding drainage, flooding with good quality river or irrigation water, and measures such as lime and phosphate applications will enable at least part of the Sulfaquepts to produce a reasonable rice crop. Nevertheless, such a delicate management pattern is not possible, or is uneconomic in many instances.

  Injudicious development of Sulfaquepts for cropping has led to many failures and to wastes of effort and money. The trend of trying large-scale development is still going on in areas where Sulfaquepts and their precursors, Sulfaquents, are extensive, e.g. in the Mekong River delta, and in the coastal areas of Sumatra and Kalimantan.
- *Halaquepts* (Gleyic Solonchaks): The Halaquepts are the Aquepts that are saline in the upper parts of the profile. With paddy cultivation the salt may leach from the soil surface during the growing season, but during the dry season the salt may accumulate at the surface. Such soils occur in coastal marine areas, and also on inland alluvial plains of the drier monsoonal climates. Often, such soils are best for irrigated rice because their use for irrigated dryland crops enhances further salinization.
- *Andaquepts:* The Andaquepts have developed on so-called pyroclastic material, mainly ash of volcanic origin. Such soils are rich in amorphous clay (allophane) and have a low bulk density. They occur in volcanic areas, usually on foot slopes and in valleys where sediments include volcanic ash. The Andaquepts are common rice-growing soils in Japan, but only a few are seen in the intertropical areas with active volcanism, e.g. the Philippines and Indonesia. As with better-drained soils on pyroclastics, the Andaquepts have high phosphate fixation, which often limits production.
- *Tropaquepts*[3] (Eutric, Calcaric, Dystric, and Humic Gleysols, *pt*.): The Tropaquepts are the Aquepts of the continuously warm areas, where soil temperature at the 50-cm depth differs by less than 5°C between summer

[3]Note that the soil temperature regime used in *Soil taxonomy* as a diagnostic characteristic at a high level of classification (great group, suborder) was not introduced in the FAO-Unesco legend. This means that for many units in the *FAO-Unesco soil map of the world* legend there is a tropical and nontropical variant in *Soil taxonomy.*

and winter. Tropaquepts are the most important rice-growing soils in the major and minor alluvial valleys and coastal plains in Asia below the 17th parallel. They are a few hundred years old or older, and not subject to rapid accretion by new soil deposits.

The Tropaquepts show a wide range of characteristics and, consequently, considerable variation in productivity for rice. The variations, partly expressed in the different subgroups and at the family level must be studied further to complete the classification of intertropical Aquepts that play an important role in rice growing.

The Tropaquept great group contains subgroups that are transitional to severely acid sulfate soils (sulfic subgroup), to Histosols (histic subgroup), and to Vertisols (vertic subgroups). On other continents, the use of Tropaquepts for rice growing is increasing, but considerable areas are still available for the extension of the rice crop, especially in the intertropical zone of Latin America.

- *Haplaquents* (Eutric, Calcaric, and Dystric Gleysols, *pt.*): The Haplaquepts are the Aquepts from the zone where soil temperature at the 50-cm depth differs by more than 5°C between winter and summer. In Asia the limit between Tropaquepts and Haplaquepts, which are morphologically similar, is roughly the 17th parallel, although that limit has not been determined with any precision. Data from Thailand (Rice, 1969) indicate that in the northern provinces, soil temperature regimes of Aquepts growing wetland rice are mainly nontropic, hence those soils would be predominantly classified as Haplaquepts. In the southern part of Thailand, soils with a similar morphology and land use are Tropaquepts.

  In Bangladesh (Brammer, 1971b) and Japan (Matsuzaka, 1971), the soil temperature regime disqualifies the soils for *Trop* great groups. The same is true for the soil areas north of Hyderabad in Andhra Pradesh, India (Murthy, 1978).

  Haplaquepts are, therefore, the major wetland rice-growing soils in the zone with a distinctly cooler winter climate. They are dominant on all larger alluvial and deltaic plains of that zone, and also occur extensively in inland valleys and on lower slopes.

  The variation in soil properties in the Haplaquepts is even greater than that in the Tropaquepts. Base saturation, particularly the presence of free lime, varies both with source of the parent material and with climate, i.e. amount of leaching. Medium to low base saturation in Aquepts is reported in southern China and in Japan. High base saturation (more than 50% by NH_4O Ac in the subsoil) is most common while the soils are calcareous, where the climate is more arid or where the soil is flooded with water high in bases.

The largest surfaces of calcareous Aquepts are found on the Ganges floodplains.

Most acid Haplaquepts are found in coastal areas where soils belonging to the sulfic subgroup (acid sulfate soils) have pH values between 3.5 and 4.0 in the subsoil. Other subgroups of Haplaquepts are transitional to the order of Mollisols and Vertisols. Even though all Haplaquepts are hydromorphic and thus favorable for rice from a soil-water point of view, their rice-production capability ranges from excellent to moderate, or even marginal, depending on site-specific morphological, chemical, and hydrological conditions. Most fine loamy to clayey, moderately to highly saturated Haplaquepts are well suited for rice growing,

- *Humaquepts* (Humic Gleysols): The Humaquepts are nearly black or peaty, wet, acid Aquepts of mid-latitudes. They occur as spots in some rice-growing lands dominated by Haplaquepts. The Humaquepts' quality is restricted by soil acidity and poor drainage.

ANDEPTS (Andosols). The Andepts are usually dark-colored soils with a clay fraction dominated by amorphous material (allophane, a noncrystalline aluminum silicate) and with low bulk density (less than 0.85). Most Andepts have a high organic matter content in the surface soil. Soils composed mainly of volcanic ash or cinders are also included in the suborder.

With few exceptions, rice-growing Andepts are of volcanic origin and appear mainly in zones of active volcanism (Japan, Philippines, Indonesia), usually on the middle and higher parts of volcanoes in the intertropical areas. Andepts also occur on lower, undulating plains as in Japan. Their topography is rarely flat and rice on these soils is mainly of the pluvial type. The units Aquic Ando upland soils and Aquic Nonhumic Ando upland soils of Matsuzaka (1969) are in use for irrigated rice.

In other areas with Andepts, i.e. Java and Luzon, there is a definite trend toward construction of pluvial or irrigated paddies on these soils. Few Andepts are reported from continental Asia.

The subdivision of rice-growing Andepts is based on the base saturation. Eutrandepts have a base saturation of more than 50%. They occur mostly in climates with a pronounced dry season (e.g East Java) or on ashes rich in weatherable minerals. Dystrandepts, which are the majority of rice-growing Andepts, have less than 50% base saturation and are more common in the wetter climates. Most Andepts are highly deficient in phosphorus, which is strongly fixed.

TROPEPTS (Cambisols, *pt.*). The Tropepts are the well-drained Inceptisols of the warm regions, where the variation in soil temperature at the 50-cm depth is less than 5°C between the warmest and coldest months. Tropepts occur in the same areas as Tropaquepts. Tropepts occur in widely varying landforms and the range of soil characteristics is considerable within the suborder. Of most importance for rice are the Tropepts on alluvial plains and on alluvial terraces in positions where groundwater is neither permanently nor periodically close to the surface. They are found in association with wetter Aquepts, mainly

Tropaquepts, from which they differ by browner colors in the subsurface horizons.

Tropepts in the lowland position in Asia are extensively used for pluvial-anthraquic rice land, and irrigation of Tropepts is expanding rapidly. Other Tropepts occur in hilly terrain, often on surfaces that have been rejuvenated by deposits of colluvial materials on concave slopes: Such sloping Tropepts occur mainly in small, localized spots in the landscape, and their use is similar to that of the surrounding soils that nave undergone less rejuvenation. On the *FAO-Unesco soil map of* the *world,* the largest consolidated area of Tropepts (Humic and Dystric Cambisols) in Asia is found on the west coast of Sumatra, where they are associated with Andepts. In Asia, pluvial rice land is common on undulating to steep Tropepts and such soils are used in shifting cultivation pattern with rice as a component. Some of the sloping Tropepts are pluvial-anthraquic or irrigated paddies.

Outside of Asia, particularly in West Africa, rice is grown on the lower-slope Tropepts, mostly where groundwater is periodically high (Aquic subgroups). The West African cropping pattern is shifting cultivation, and rice is often mixed with other crops such as corn and cassava.

Rice is grown most extensively on three great groups in the Tropept suborder:

- *Ustropepts* (Eutric, Calcic, Vertic Cambisols, *pt.*): The Ustropepts are from the regions without a pronounced dry season. They have a high base saturation below 25 cm. They are rare in the rice-growing zones, and are frequently connected with landscapes dominated by more basic rocks (limestone, basic volcanics, young alluvial).
- *Dystropepts* (Dystric, Ferralic Cambisol. *pt.*): The Dystropepts have a low base saturation below 25 cm. Few. occur in young and semirecent alluvial deposits. They are found mainly on sloping land where the soil is derived from the intermediate and acid rocks. Most rice on Dystropepts is grown on pluvial rice land in a shifting cultivation pattern, but there are a few cases of terraced paddy lands. e.g. in West Java.
- *Humitropepts* (Humic Cambisols): The Humitropepts are rich in organic matter, low in base status, and are found mainly in higher altitudes of hilly and mountainous land. They are rarely used for rice.

OCHREPTS (Cambisols, *pt.*). The Ochrepts are Inceptisols in areas with a soil temperature difference of more than 5°C at 50-cm depth between the warmest and the coldest months. Ochrepts occur outside of the continuously warm intertropical areas and in a wide range of moisture regimes (ustic to perudic), physiographic positions (flat alluvial plains to steep lands), and parent materials.

In Asia, roughly north of the 17th parallel, Ochrepts are important rice soils, especially on the rice-growing plains of northern India and eastern China. There they occur on river and coastal formations that are not regularly rejuvenated by silt-bearing floods. Their relatively good drainage excludes them from the Aquept suborder.

On the *FAO-Unesco soil map of the world,* extensive surfaces of Cambisols, which are equivalent mainly to Ochrepts of *Soil taxonomy,* are indicated on the wide plains of the Ganges River system in northern India. On those soils both pluvial-anthraquic and irrigated rice cultivation are widespread.

Where the topography is rolling and hilly, most consolidated surfaces of rice-growing Ochrepts are small. Extensive areas of Ochrepts used for shifting cultivation, which includes pluvial rice, are reported in eastern Bangladesh and the adjacent hilly areas of Burma and India (Brammer, 1971a). In Asia, the lower-slope Ochrepts are frequently terraced and may be irrigated, but pluvial rice land is dominant on the higher and more sloping landscape.

There are three major rice-growing great groups in the Ochrepts suborder.

- *Ustochrepts:* The Ustochrepts are mainly soils of the recent alluvial plains and semirecent river terraces that have a pronounced dry season. These are major rice soils, especially the somewhat wetter (aquic) subgroups. Many transitional soils are found among the Ustochrepts, e.g. transitions to Fluvents and to Vertisols.

  Rice is not often grown as a dryland crop on Ustochrepts because of the unfavorable rainfall regime. Pluvial anthraquic paddies, however, are widespread where the soils have a flat topography and where sufficient water can be retained for a single rice crop. Yields are usually low, even though the quality of the soils is mostly medium to high. Considerable intensification of rice growing and higher rice yields are seen where irrigation water is available.
- *Eutrochrepts:* The Eutrochrepts are Ochrepts of the humid climates - no pronounced dry season — that have a high base saturation in the subsoil between 25 and 75 cm. Rice-growing Eutrochrepts in lowlands are confined to somewhat better drained alluvial plains, inland valleys, and terraces where the sediments are calcareous, or derived from highly saturated soils in the catchment areas. Eutrochrepts are reported in such positions in Bangladesh (Brammer, 1971b) and in adjacent areas of Burma and India. These low, flat Eutrochrepts are to a large extent used for paddy rice (pluvial-anthraquic, phreatic-anthraquic, irrigated). Most Eutrochrepts in China, Korea, and Japan are fully irrigated.

  Eutrochrepts occur in spots in hilly areas where the parent material is basic. In Southeast Asia where the soils are deep enough and not too steep, such spots are often used for pluvial rice in a shifting cultivation pattern.
- *Dystrochrepts:* Dystrochrepts are Ochrepts of the humid climates — no pronounced dry season — that have a low base saturation in the soil profile. Rice-growing Dystrochrepts, usually the hydromorphic (aquic) subgroups, are widespread in plains and valleys, e.g. in Bangladesh (Brammer, 1971b). The parent material in such positions is either composed of more acidic allu-

vial or colluvial sediments, or the soils are old enough to have lost their high base status through leaching.

Sloping and hilly Dystrochrepts are developed mainly on acid parent materials from sedimentary and metamorphic rocks. They are widespread in Japan, but only in the south incidental use is made of them for pluvial rice. On the hilly Dystrochrepts that are not too stony or steep, e.g. in eastern Bangladesh, Burma, Laos, northern Vietnam, and northernmost Thailand, pluvial rice in a shifting cultivation pattern is grown.

UMBREPTS. The Umbrepts are acid, freely drained, organic-matter-rich Inceptisols, found mainly at high altitudes. Few are used for rice. Brammer (1971a, b) found Umbrepts (Black Terai Soils) in the old Himalayan Piedmont plains in the north of Bangladesh where transplanted rice is grown. That zone of rice-growing Umbrepts extends westward in India.

Mollisols (Mollic Gleysols, *pt.* Kastanozems, Chernozems, Rendzinas, Greyzems, Planosols, *pt.*)

The central concept is that Mollisols developed in temperate, subhumid-to-subarid climates of the mid-latitudes under a grassland vegetation.

Little rice is grown on Mollisols in the zone of their widest distribution. From the point of view of soil genesis, Mollisols are believed to have developed under a grass vegetation, but some formed under forest, influenced by basic parent materials, mainly chalk or marl, and, as was recently discovered, also by basic pyroclastic sediments. Recent studies of the soils in the warmer climates indicate, that Mollisols are much more common in the tropical zone than was previously believed.

The main diagnostic characteristics of Mollisols are a thick, dark-colored, well-structured surface horizon with high humus content (mollic epipedon) and a high base saturation throughout the profile.

Most rice-growing Mollisols are in alluvial plains and valleys, usually recent or semirecent and with base-rich parent materials dominating. Spots of such lowland, rice-growing Mollisols were found in several Southeast Asian alluvial plains, e.g. in Bangladesh (Brammer 197lb) and central Thailand (van der Kevie and Yenmanas, 1972). Wet Mollisols are reported in the irrigated rice areas in Texas (Westfall, 1975) and California, USA (Flach and Slusher, 1978), in lowland rice areas of Asiatic Russia (Kostenov, 1975), and in lowlands of areas dominated by young volcanic formations e.g. Luzon and eastern Java (author’s observations).

In some intertropical areas, Mollisols in better drained upland positions grow dryland rice, frequently as the main food crop on lands in continuous cultivation. The single major area of pluvial, rice-growing Mollisols we observed was in southwestern Luzon, around Lake Taal. The Mollisols in that area are on young pyroclastic sediments.

The inherent quality of Mollisols for rice growing is high.

AQUOLLS (Mollic Gleysoils, *pt*). The Aquolls are the wet Mollisols — water saturated during part of the year — that occur in the lower aspects of the landscape, mainly in alluvial plains and valleys. In Asia, most of the Aquolls are in phreatic-anthraquic or fluxial rice lands. Some Aquolls that are periodically deeply flooded are used for deepwater rice. In calcareous Aquolls, as we observed in the Philippines, moderate to severe zinc deficiency may occur.

UDOLLS. The Udolls are freely drained Mollisols in climates too humid for the formation of a horizon enriched in calcium carbonate (calcareous horizon). The lower-elevation Udolls (aquic subgroup) are in phreatic-anthraquic or irrigated paddies, but on the higher elevations intensive cultivation of dryland rice is found. With sufficient rainfall, rice yields are high under optimum management. De Datta and Beachell (1972) reported 7 t/ha from experiments on Udolls in Batangas, Philippines. Unfortunately, the total area of intertropical Udolls available for rice growing is limited.

Oxisols (Ferralsols, Gleysols. *pt*)

The Oxisols are strongly weathered, mainly reddish and yellowish soils of the tropics and subtropics. They are thought to be of great age, having developed on stable landscapes that have been either not or only slightly influenced by erosion. According to the present definition in *Soil taxonomy,* the master horizon in Oxisols is the oxic horizon, characterized mainly by low exchange capacity of the clay, lack of weatherable minerals, and absence of clay illuviation. Structure in the oxic horizon is usually weakly developed, but the fine structure units or peds are stable and the soil is permeable.

It was thought until recently that Oxisols were dominant in the humid and subhumid equatorial areas. Thus, large surfaces of Ferralsols, the equivalent of Oxisols of *Soil taxonomy,* occur on the FAO-Unesco soil maps of South America and Africa. But recent studies have strongly de-emphasized the order. Whereas large surfaces of Oxisols do occur in South America, especially in Brazil, it is now known that their extent is much less than originally assumed. The same is true for Africa, where considerable areas indicated as Ferralsols (Oxisols) on the FAO-Unesco soils map are now known to be mainly Ultisols. This newly acquired knowledge has been applied to the Asian sheets of the FAO-Unesco soil map, and the surface of Oxisols is strictly limited to a few old terrace formations and a few volcanic areas of great age, e.g. the highlands of southern Vietnam and in the wet parts of insular Southeast Asia.

It is not yet clear whether certain dryland soils in the continuously wet (perudic and udic) equatorial forest areas should be classfied as Oxisols or Ultisols, e.g. certain forest areas in Malaysia, Indonesia, and in the basins of the Congo River zone (Zaire), and the Amazon River (Brazil). The probability is that most of these soils are Ultisols transitional between Ultisols and Oxisols.

The Oxisols are not of great importance for rice growing. Shifting cultivation of rice on Oxisols on old basalts is of importance on the high plateaus in southern Vietnam and in similar positions in Indonesia. These soils belong mainly to the suborder Ustox because they have a pronounced dry season.

On the larger areas of Oxisols in South America, especially in Brazil, there is mechanized rice farming of newly cleared Oxisols. Dryland rice is grown as the first crop for 2 years, after which the land is used for other crops or for pasture.

Spodosols (Podzols)

The Spodosols, which occur only sporadically in the climatic zone where rice will grow, are formed mostly in quartz-rich sands and are virtually devoid of weatherable minerals. All rice-growing Spodosols are formed under a wet equatorial climate on coastal or riverine sand. Leaching has developed a bleached subsurface horizon and a horizon of accumulated organic matter. Rice cultivation on Spodosols is marginal. In equatorial Southeast Asia, some rice is grown on Spodosols where natural flooding and high groundwater occur during the growing season.

Ultisols (Acrisols, Dystric Nitosols, Planosols, *pt.)*

The Ultisols, like the Alfisols, show marks of clay translocation and accumulation in an argillic horizon. The main difference between Ultisols and Alfisols is in the base saturation of the subsoils, which is lower in Ultisols. Subsidiary differentiating characteristics are a low subsoil pH, a lack of readily weatherable minerals, and the presence of low-activity clays (kaolinite, sesquioxides), which dominate the clay complex more often than they do in Alfisols. Ultisols are, hence, developed to a further stage than the Alfisols.

The original concept of Ultisols, developed mainly in the warm-temperature southeastern United States, was one of soils on older, stable surfaces, not influenced by rejuvenation due to erosion or deposit of glacial sediments. It is now known, however, that in the tropical and subtropical areas, Ultisols dominate in most higher rainfall zones, and that in their zone of maximum extension they are not confined to older surfaces alone. In fact, Ultisols occur over a wide range of physiographic positions and on many kinds of parent materials and are one of the most widespread soils in the rice-growing areas of the world. The Ultisols are surpassed in importance for rice growing only by Inceptisols and, possibly, by Alfisols.

Where rainfall permits, Ultisols are the most important soils in pluvial rice land under a shifting cultivation pattern, both in Asia and in West Africa. But in Asia considerable surfaces of less sloping Ultisols have been leveled and bunded for a paddy type of rice cultivation, mostly pluvial or phreatic but increasingly irrigated. Many of the irrigated *sawah* terraces on moderate to steep slopes in Java are on deep Ultisols that developed on volcanic parent materials. This type of land use is also found on various parent materials in other areas of intensive rice cultivation, such as in the wet zone of Sri Lanka.

AQUULTS (Gleyic Acrisols, Plinthic Acrisols *pt.;* Dystric Planosols, *pt.*). The Aquults are the periodically or permanently wet Ultisols: gray to olive-gray, on older river and marine terraces and in other wet places where the transported parent material is derived from surrounding higher areas dominated by Ultisols.

In Asia, those soils are predominantly used for rice. Most are rainfed, but an increasing proportion is irrigated. Yields with low-level management are rarely higher than 1.5 t/ha, and even with a high level of management — which includes fertilizer — rice yields remain generally below those on similarly wet but less leached soils of other orders.

High-input rice cultivation often is not sufficiently economic on Aquults, the main reason why modern rice technology has not been successful on these soils under the prevailing socioeconomic conditions in Southeast Asia. For example, many Aquults of the broad, late Pleistocene terraces of the Mekong River in Thailand, Cambodia, and Vietnam are not highly productive even with good irrigation and high-level management. The same is true for the Aquults on other river and marine terraces, such as those on the east coast of peninsular Malaysia. Outside of the humid parts of Southeast Asia, Aquults are found in similar positions on older river terraces of the humid areas where rice is grown. In the humid parts of West Africa, the Aquults are increasingly used for rice on land of the phreatic or fluxial type (swamp rice) without water control.

Rice is commonly grown on six great groups of the Aquults:

- *Plinthaquults:* Plinthaquults are Aquults in which iron-rich material, which will harden after drying (plinthite), is found at a shallow depth. These soils are commonly found on the broad terraces of northeastern Thailand. It is speculated that in these soils iron toxicity induced by interflow occurs locally (see Chap. 6).
- *Fragiaquults:* Fragiaquults are Aquults with a brittle, poorly permeable layer or horizon (fragipan) in the profile. These soils are reported from West Java.
- *Albaquults:* The Albaquults are Aquults with an abrupt transition between the sandy surface horizons and the clayey, subsurface, argillic horizon. Such soils are reported from Indonesia, where they are classified as *Planosols* in the national soil classification system. They also occur locally on older terrace formations of continental Southeast Asia, e.g. on the Mekong River terraces. The Albaquults, like the Fragiaquults, are problem soils for rice, with a generally low productivity and a low inherent fertility status.
- *Paleaquults:* Paleaquults are soils with a thick argillic horizon and with a low percentage of weatherable minerals. Many of the rice-growing Aquults belong to this great group. Their quality for rice growing varies from marginal when sandy, to moderate when dominantly clayey, but is never high.
- *Tropaquults and Ochraquults:* Two great groups of the Aquults have either a thinner argillic horizon or more than 10% weatherable minerals in the upper

part of the argillic horizon. They are, hence, usually found in somewhat younger parent materials. Their inherent production capacity for rice is higher than that of the previously discussed Aquults, but only scanty data are available in this respect.

Tropaquults are Aquults of the warm climates, where the soil temperature difference between the warmest and the coldest months at a 50-cm depth is less than 5°C. They occur in the continuously warm intertropical areas; their extent is limited.

Ochraquults are Aquults of the climatic zone with a pronounced difference between summer and winter soil temperature. They have an argillic horizon that is thinner than that of the Paleaquults or, alternately, have a higher content of weatherable minerals than the Paleaquults.

HUMULTS (Humic Acrisols, Humic Nitosols, *pt.*). The Humults are more or less freely drained Ultisols with a high organic matter content (more than 12 kg/m^3). In the world's rice-growing zone, such soils almost exclusively occur on materials derived from basic rocks, such as amphibolite, basalt, etc. Part of the steep terraced *sawahs* in the volcanic areas of western and middle Java are Humults that belong to the great group of Tropohumults. Humults in the volcanic highlands of Sumatra and in southeastern Burma (Shan states) are used for rice grown in shifting cultivation systems.

UDULTS (Acrisols, *pt.* Dystric Nitosols). The Udults are Ultisols with a udic (wet) soil moisture regime. They occur where rainfall distribution is such that soil profiles below the surface soil do not completely dry for long periods.

Udults commonly occur in undulating to steep upland positions on a wide variety of parent materials that are most commonly medium-acid or acid.

Gently sloping to flat Udults are found mainly on older sedimentary formations of the Tertiary or Pleistocene age. Among freely drained soils in the moist subtropics and tropics, the Udults form the most extensive single suborder. A large proportion of the dryland rice of Asia and other continents is on these soils. That rice crop is grown in a shifting cultivation pattern, but in small areas it is also on terraced, irrigated or phreatic-anthraquic paddy lands.

The dominance of shifting cultivation is undoubtedly related to the generally poor fertility of the Udults. The nutrient level of Udults is low, and a good proportion of the nutrients is stored in the aerial parts of the plant cover (forests or man-made savanna). After clearing and burning, sufficient nutrients are restored to the soils to grow one rice crop or, rarely, two crops.

Without water control and high-management inputs, including fertilizers, the Udults will not grow rice continuously. In most cases, the aquic subgroups are preferred for rice and it is on such soils that more intensive, continuous rice growing will make the most progress in phreatic-anthraquic and irrigated rice fields.

Under high-input management, yields of rice on Udults can be greatly increased. In Japan, paddy lands on Hapludults (aquic yellowish-brown and reddish-brown dryland soils; Matsuzaka, 1969) produced from 4 to 5 t/ha.

There are four major rice-growing great groups of the Udults.

- *Paleudults* (Acrisols, *pt.;* Dystric Nitosols, *pt.*): The Paleudults have a uniform, deep argillic horizon in the upper 150 cm, which has less than 10% of weatherable minerals. They occur mainly on gently sloping to flat surfaces, but in the humid tropics are also found on steeper terrain where weathering is deep. Rice and other crops on Paleudults are grown mainly in a shifting cultivation pattern in areas with a predominance of low-technology agriculture. High-technology, mechanized, pluvial rice cultivation is currently being introduced on large farm units in West and Central Africa and in South America. The results frequently are marginal, especially in regard to long-term sustained land use.

  The aquic subgroups have a somewhat higher quality for rice due to a better water regime and their position on lower slopes. Part of those soils are terraced.

  The rhodic subgroup, characterized by dark colors — usually dark red to a great depth — developed from basic, iron-rich parent materials such as basalts, amphibolites, and limestones.
- *Rhodudults* (Dystric Nitosols, *pt.*): The Rhodudults are Udults characterized by dark colors (mainly dark red) in all horizons. They are dominantly developed from basic parent materials, e.g. basalts, and are found mainly in volcanic areas (southern Vietnam, Philippines, Java and Sumatra, Western Cameroun). Together with the rhodic subgroup of Paleudults, the Rhodudults have a distinctly better quality for rice growing than the Paleudults and are preferred for a more intensive shifting cultivation pattern. The Rhodudults' structural stability is distinctly superior to that of other Udults; they have been terraced on steep slopes and are used for irrigated paddy as in Java, mainly in the western part of the island. Under such conditions, sustained, intensive land use for rice and subsidiary crops is possible. The steep-land agriculture in Java is one of the most intensive types of land use in existence.
- *Tropudults* (Orthic and Ferric Acrisols, *pt.*): The Tropudults are Udults of the continuously warm intertropical areas and do not belong to any of the previously mentioned great groups of Udults. The soil temperature differs less than 5°C at a 50-cm depth between the warmest and the coldest months. These soils occur mainly in association with the warm-area Paleudults, usually on rejuvenated parts of the landscape on steep slopes. They differ from Paleudults either by a higher content of weatherable minerals or by a thinner argillic horizon, or both. The extent of rice-growing Tropudults is limited. Rice is grown in a shifting cultivation pattern, but in a few places Tropudults are seen in paddies.
- *Hapludults:* The Hapludults are comparable with Tropudults, but they occur in areas with more than 5°C variation in soil temperature at a 50-cm

depth. In generally cooler climates soil profile formation and leaching were less extreme, hence more Hapludults — and less Paleudults — are found toward the cooler zones. Much of the dryland rice above the 17th parallel in eastern Asia is grown on Hapludults. In southeastern China and in Japan, some of the lower-elevation Hapludults are in use for terraced and irrigated rice lands.

USTULTS (Acrisols, *pt.;* Dystric Nitosols, *pt.*). The Ustults are the Ultisols of warm regions that have high to moderate rainfall and one or sometimes two pronounced dry seasons. The Ustults are important soils in monsoonal rice areas and are found both in hilly areas, as in the drier parts of Southeast Asia, or on older terrace formations — mainly those in which the original sediment was derived from acidic rocks and from hilly Ultisols. The Ustults often occur in transitional zones between the wetter Udults and the drier, more highly saturated Ustalfs. Ustults are found in such transitional zones in West Africa and in southwest India, where they dominate on older surfaces and on the more acidic rocks.

Large areas of Ustults, which are steep or rocky to gravelly, are not cultivated at all, although due to population pressure some of such lands on the lower slopes are now being cultivated for one to two seasons, after which they return to bush for an indefinite time. Soil deterioration in such injudiciously used land is serious. Ustults on older terrace formations in Asia (mainly in the lower Mekong River basin) are partly in use for pluvial-anthraquic rice land, but actual and potential yields on such lands are limited.

There are three main rice-growing great groups in the Ustult suborder:

- *Paleustults:* The Paleustults are deep Ustults with less than 10% weatherable minerals in the upper part of the argillic horizon. Paleustults are most important on old river terraces and on other gently undulating to flat old surfaces. Pluvial rice is grown on these soils in a shifting cultivation pattern in Asia and Africa.

  On the moist, aquic subgroups, phreatic-anthraquic rice land is common in Asia, e.g. on the terraces of the lower Mekong River. A small proportion is irrigated.

  In Africa, the use of Paleustults for dryland rice is common in those areas where the rainy season is sufficiently regular. Nevertheless, in one of the older rice-growing areas, Casamance in southern Senegal, the tendency is distinctly from such well-drained Paleustults toward poorly drained soils.
- *Rhodustults:* The Rhodustults are Ustults that are dark colored (usually dark red) in all horizons. They have a thinner argillic horizon than the Paleustults, or have an appreciable amount of weatherable minerals. They are found mainly in high positions on hills and plateaus, where they have developed from more basic rocks such as basalts, limestones, and calcareous shales. Rhodustults in the high plateaus of the drier monsoonal areas of

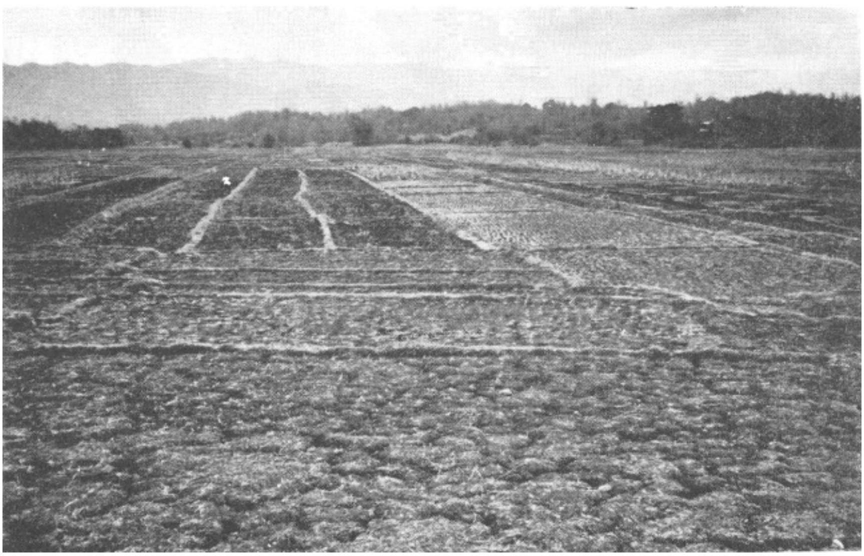
Southeast Asia are under intensive shifting cultivation, and dryland rice is the main crop.

- *Haplustults:* The Haplustults are dominant Ustults on rolling to steep land in the rice-growing zone of continental Asia; they occur mixed with other Ultisol great groups and become more important toward the cooler climates. Most frequently, the Haplustults are only marginally suited for any form of agriculture, but when not too steep or stony they are used for shifting cultivation with rice as a component. To date in the existing systems, where the fallow period is sufficiently long, not much damage has been done to these soils. But with increasing population pressure, soil erosion and deterioration of the Haplustults are rapidly becoming a serious problem. That is happening at an ever accelerating rate in some of the hilly areas of India.

Vertisols (Vertisols)

The soils of the order Vertisols have long been recognized as a morphologically homogeneous unit, and a score of names are used for them, e.g. Regur in India and Grumusol in Southeast Asia. Dudal (1963) gives an excellent review of their characteristics and agricultural properties.

The Vertisols are characterized by fine or very fine clay profiles that, without irrigation, have deep, wide cracks at some time of the year (Fig. 3). In addition, alternate swelling and shrinking cause movement of the soil material both at



4. This paddy field in a Vertisol landscape (Ilocos Norte, Philippines) shows deep wide cracking during the dry season (Ustert).

the surface and inside the profile, resulting in such characteristic features as irregular microrelief (gilgai) and the occurrence at some depth of a polished and grooved surface (slickensides), produced by one mass of soil sliding past another. The cracking implies that they occur in environments with seasonal drying of the soil. Thus, they are not found in the perudic, continuously wet climate in the equatorial regions, nor are they widespread in the udic climate where the soils dry out for limited periods only.

Rice-growing Vertisols have their maximum extension in the ustic climates. There, soil profiles dry for more than 90 consecutive days (unless irrigated), but there is a distinct surplus of water for at least 60 days. The most important areas of rice-growing Vertisols are found on the Deccan Plateau of central India and in the basins of the Irrawaddy and Chao Phraya rivers, respectively, in Burma and Thailand, but they form important components on other rice-growing plains in Asia, Africa (middle valley of the Niger River, Chad Basin, and the Nile River valley of the Sudan), the United States, and Australia. Outside of Asia, however, rice growing on Vertisols is relatively recent and is not widespread.

The greater proportion of the rice-growing Vertisols is found on a flat to slightly depressed topography, with natural slopes not exceeding 1%. In this position, most Vertisols are formed from transported (alluvial or colluvial) sediments, derived mainly from such basic rock types in the catchment areas as calcareous sedimentary rocks, basic igneous rocks, basalts, and volcanic ash. A small proportion of Vertisols under rice are also found on somewhat steeper, usually lower slopes, where the land is terraced and often irrigated.

While the nutrient status of Vertisols places them among the more fertile rice-growing soils, their physical behavior often poses problems. In the drier climates, use of Vertisols for rice without irrigation is problematic, mainly because seedbed preparation under such circumstances is difficult and strongly dependent on the rainfall pattern. Thus, many of the topographically higher Vertisols in the central plain of Thailand become marginal phreatic or pluvial rice lands. Even where water is available, either from more abundant rainfall, from flooding, or from irrigation, seedbed preparation has to be done under exactly the right moisture status of the soil, i.e. neither too wet nor too dry because in both cases the workability of the Vertisols is unfavorable. This workability factor and, in certain cases, other factors such as micronutrient deficiencies (e.g. zinc) and a tendency toward salinization explain why few Vertisols are used for growing rice.

There are great differences among Vertisols in the structure of the surface horizons. Some Vertisols have a surface mulch of fine and medium granules, but most have unfavorable structure for seedbed preparation. The surface differences are related mostly to soil management; the differences are not stable and a Vertisol with a favorable surface mulch in one year may be crusty and hard the next year. Because of their variability under soil management, the management characteristics cannot be used for subdividing Vertisols into lower units.

Most Vertisols in use for anthraquic rice cultivation have an unfavorable surface structure when the soil dries after the harvest of the rice.

Three suborders of Vertisols are used for rice growing.

TORRERTS. The Torrerts are Vertisols with cracks that stay open most or all of the year unless the soil is irrigated. Some irrigated rice is grown on such soils in the drier parts of the Sudan zone in Africa.

UDERTS. Uderts are Vertisols with cracks that open and close several times in a year, but do not remain open for more than 90 days in most years. Rice-growing Uderts are not widespread; they are found occasionally on basic parent materials in the wetter (udic) rice-growing areas, e.g. Luzon in the Philippines. Most Uderts used as irrigated paddy lands are highly productive, and some of the highest recorded rice yields were obtained on such soils.

USTERTS. The Usterts are Vertisols with cracks (Fig. 4) that open for more than 90 days unless the soil is irrigated, but close during the wet season for more than 60 consecutive days. The Usterts are the most widespread Vertisols and are extensive on the Deccan Plateau of India where they are used for paddy rice, both bunded and irrigated. Two-crop irrigated paddy rice is found mainly on the Usterts in low areas, while the somewhat higher paddies usually produce only one wet-season rice crop.

Outside of India, rice-growing Usterts are much less widespread, but small areas occur in Thailand (central plain), Burma (upper Irrawaddy River valley), Indonesia (Middle and East Java), and in the ustic parts of western Philippines.

CHAPTER 5

Soil-forming processes in aquatic rice lands

WET CULTIVATION OF RICE superimposes changes on the original or *natural* soil profile. Those changes are often slight and restricted mainly to the surface soil. The changes may also be temporary, with the soil reverting to its original condition between crops in the cropping cycles. On the other hand, the cumulative effect of seasonal inundation cycles is often significant and permanently alters the original soil profile. Important permanent soil modifications may also result from management practices such as terracing and scraping.

TEMPORARY CHANGES IN SURFACE SOILS

The most important temporary changes in soils growing flooded rice are those associated with puddling, and with chemical reduction and oxidation.

Puddling

Puddling, the tillage of soil while water is standing on the field, is commonly associated with rice growing (Fig. 1). The main advantages of puddling appear to be weed control and greatly reduced water percolation. Puddling leads to several temporary changes in the surface soil. There is partial or complete destruction of soil aggregates due to swelling of colloids and to mechanical impact. Macropores disappear and micropores increase greatly. The micropores present themselves as water hulls around soil aggregates and individual particles.

With increased microporosity, the water-holding capacity of the puddled soil increases. That is especially so if the swelling 2:1 clay minerals are dominant, but is much less so in soils dominant in kaolinitic clay. By increasing water retention, the puddled surface soil assumes characteristics comparable with those of freshly deposited soft muds, and has low cohesion due to the low ratio of soil to water.

The properties of a puddled soil change during the growing season. After puddling, the mud settles and the original moisture content decreases. Settling is rapid in sandy soils and in finer-textured soils with a kaolinitic clay mineralogy. Despite continued flooding, the soil moisture content may further decrease as soil water is extracted by the rice roots. The heavy marine clay soils in Surinam are an example of this; the water content of the puddled topsoil

1. Puddling (the wet tillage of rice lands) as in this inland valley in Burma, destroys soil aggregates and enhances formation of a traffic or plow pan. Both processes reduce water losses by percolation. (FAO photo by I.W. Kelton)

decreased from a range of 90 to 100% to a range of 20 to 60% during the growing season, and the packing density of the particles increased accordingly (Scheltema, 1974). A vesicular structure often develops in puddled clayey soils as a result of trapping of gases formed during soil reduction. The presence of fine clay layers and algae at the soil surface restricts the escape of the gases and contributes to the formation of vesicles (Fig. 2).

After drainage of flooded fields, æration and drying are generally more rapid in well-aggregated soils than in puddled soils. Therefore, puddling helps keep the surface soil reduced during brief periods of water shortage. Following a long dry period, however, the soft mud will crack and dry to a stiff paste. Cracking is strong if expanding clay minerals are present, but may be appreciable even in kaolinitic soils. Therefore, inadvertent drainage for long periods, which often happens in many rice-growing areas, will change the structure of the puddled topsoil for the rest of the growing period. Such a change can have important consequences such as increased water loss through percolation and increased nutrient loss.

During a dry fallow period following puddling, clayey soils are reaggregated through drying and cracking. The postflooding tilth of such soils is often unfavorable because of hard, medium- to large-sized, blocky structural units.

In soils high in organic matter this structural deterioration is less. In the absence of a pronounced dry season the surface soil may remain a tough paste.

Soil stratification due to puddling is common in soils of medium texture where the sand fraction settles first and is covered by gradually finer silt and clay. The relative thickness of the sandy and more clayey strata depends on the original texture. In sandy soils, the clayey cover is thin, or may be even absent. In very fine clayey soils the stratification is difficult to observe. In medium-textured soils with a low organic matter content, as in northeast Thailand, the surface stratification is usually well-developed, with a fine-textured surface layer a few millimeters thick and relatively high in organic matter, overlaying 1 to 2 cm of almost pure sand. Plowing will break up surface stratification, but fragments of sandy and clayey strata persist through one or more crop cycles and give such surface soils a heterogeneous color and texture.

Reduction and oxidation

We cover the aspects of short-term chemical changes in the surface horizons of seasonally flooded soils that are important for rice growing, based mainly on Ponnamperuma's (1972) review. This step is important for understanding long-term chemical changes.

When a soil is water-saturated or submerged, the diffusion of gases into the soil mass is drastically cut and arobic organisms rapidly deplete the oxygen in

2. Gases formed during soil reduction may be trapped under a thin platy surface soil layer, causing the vesicular structure seen in this dried clod (thickness of clod is about 5 cm).

the surface soil. Thearobic decomposition of organic matter, which is normally relatively rapid in a well-ærated soil, is taken over by slower acting facultative or obligate anaerobic organisms. To oxidize organic matter, these organisms use either reducible inorganic components such as nitrate, manganese, iron oxide, and sulfate (anmobic respiration) or certain reducible organic compounds (fermentation). As a result, the soil is reduced except for a thin surface layer (0.5–10 mm) where oxygen can still penetrate. Typical end products of decomposition of organic matter in flooded soils are carbon dioxide, the lower fatty acids, methane, and ammonia, which is derived mainly from anærobic deamination of amino acids.

Soil oxygen may be depleted within a day of flooding. Nitrate disappears next by reduction to gaseous nitrogen oxides and dinitrogen. Ammoniacal nitrogen may also be lost after it is nitrified in the thin, oxidized surface layer, which acts as a sink for ammonia diffusing upward. The nitrate formed moves down into the reduced soil by diffusion and mass flow, and is denitrified. A similar sequence of events leads to nitrogen losses where there is alternate drainage and flooding.

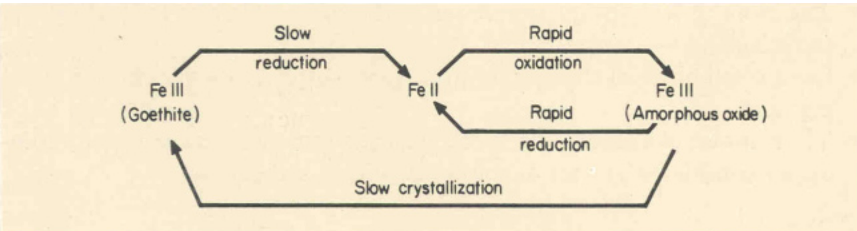
After the disappearance of nitrate, the concentration of manganese (Mn^{2+}) — and somewhat later of iron (Fe^{2+}) — often increases in the soil solution to distinct peak values during the first weeks of flooding, and then decreases to a fairly constant value. Those cations are normally balanced by bicarbonate ions (HCO^{-}_{3}) that are produced simultaneously. Acid soils high in organic matter and easily reducible iron oxides build Fe^{2+} concentrations as high as 600 mg/liter within 1 to 3 weeks of submergence, followed by a rapid decrease to levels of 50–100 mg/liter. In calcareous and alkaline soils, the mobility of Fe^{2+} is lower due to a high pH, and Fe^{2+} concentrations rarely exceed 20 mg/liter. Dissolved Fe^{2+} displaces part of the exchangeable cations leading to an increase in the concentrations of sodium (Na^{+}), calcium (Ca^{2+}), and magnesium (Mg^{2+}) in solution. In the course of soil reduction, the redox potential of the soil may drop from distinctly positive values to negative values of the order of –0.1 to –0.2 V within a few weeks of flooding.

In surface soils with an initial pH between 5 and 6, the incrtase in alkalinity (HCO_3^{-}) associated with reduction of ferric oxide to aqueous Fe^{2+} implies an increase in pH, normally from 6.5 to 7. But in calcareous and alkaline soils, less dissolved Fe^{2+} and hence less HCO_3^{-} are formed. There, the acidifying effect of accumulated carbon dioxide is more important, with a fall in pH to between 6.5 and 7. Strongly alkaline soils (pH>9) such as those in semiarid areas in northern India and Pakistan are normally low in organic matter (<0.4% C) and show little reduction after flooding. Consequently, the pH tends to remain high and rarely drops below 8.5 unless organic matter is added to the soil.

The fraction of total ferric iron reduced to ferrous iron may vary from a few percentage points to as much as 90% (Mitsuchi, 1974a). By far the greatest part of the reduced iron is normally in the solid and adsorbed form with less than 1–5% present as dissolved Fe^{2+}. Little direct information is available on the nature of solid ferrous iron. It may be partly hydrated magnetite (Fe_2O_3 nH_2O). Sulfide, phosphates, carbonate, and organic salts of iron may be involved too, while part of the ferrous iron may precipitate as $Fe(OH)_2$ interlayers of 2:1 clay minerals (Lynn and Whittig, 1966).

After drainage and æration redox potential rises from negative values to the positive values (0.3–0.6V) typical of ærobic soils, often within a few days (Whistler et al., 1974; Reddy and Patrick, 1975). But æration may be slow in puddled clayey soils, and the interior of clods remains reduced for some time after drainage. Once the puddled layer is cracked by severe drying, and reflooded, æration is more rapid during the next drainage period. Aeration causes a rapid oxidation of dissolved and exchangeable Fe^{2+} whereas other, so-called inactive forms of ferrous iron oxidize relatively slowly (Motomura, 1969). Alternate reduction and oxidation lead to the buildup of ferrous iron compounds in the surface soils that remain unoxidized throughout the fallow period (Mitsuchi, 1974a).

As a result of alternate flooding and drainage, the easily reducible ferric oxides, such as amorphous ferric hydroxides, tend to increase in the surface soil at the expense of more stable ferric oxides, such as goethite and hematite. The mechanism of the transformation of crystalline iron oxides under seasonal flooding is represented schematically as



The crystallization to goethite is much slower than the formation of amorphous oxide in the conditions described.

Oxidation of exchangeable ferrous iron produces exchangeable hydrogen, in addition to ferric hydroxide. The presence of increased exchangeable hydrogen may lead to a lowering of the soil pH and to a partial destruction of clay minerals.

The cyclic physical and chemical changes that occur in soil reflect on the morphology of the surface soils. When they are submerged and reduced, the brown matrix colors and the mottles usually present in the ærobic surface soil disappear and the soil color changes to neutral gray or bluish gray. In very sandy soils, or other permeable soils, the reduced colors may not develop or may be found only after prolonged inundation. At the surface of the reduced horizon a thin layer remains oxidized and brownish in color because of oxygen diffused downward from the air or from photosynthesizing algae.

Rusty mottling develops in paddy lands after drying and re-oxidation of reduced soil material. In medium- and fine-textured soils, in which cracks form upon drying, ferrous iron migrates from the inside of the still wet peds and is oxidized and immobilized as ferric hydroxide in the outer zone of the ped. The immobilization is frequently on the ped surface as well, thus forming distinct coatings (Fig. 2). Rice-root channels also form access routes for oxygen, and upon soil drying the channel is surrounded by a thin brownish to reddish ring, rich in ferric iron (root mottling). Within the channel, on the outside of dead roots, a thin, distinct iron oxide deposit may be found. Some of the root mottles may develop during flooding as a result of secretion of oxygen by living roots of rice or other aquatic plants. Root mottling is not exclusive for soils of paddy lands but generally develops in such soils during the period that the soil is aerated.

Root mottling in very sandy soils is less distinct and often rakes the form of diffuse brown spots within the soil mass. In acid soils that are high in ferrous iron during the flooding, the iron precipitated around the root channels can be enough to form genuine pipes of ferric oxides. Such pipes are thin and fragile in rice root channels but may be up to 5 mm in diameter around roots of larger aquatic plants.

PERMANENT CHANGES OF THE SOIL PROFILE

We treat three different aspects of soil changes:

- The more or less abrupt alterations of the soil profile due to leveling and terracing;
- Certain soil physical changes resulting from cultural practices in rice growing; and
- The complex of changes in soil chemical and mineralogical properties commonly considered as part of soil formation or soil genesis.

Leveling and terracing

The use of sloping land for paddy rice cultivation requires leveling and bunding. In nearly flat areas such as alluvial plains or natural non-incised river, lacustrine, and marine terraces, leveling affects only the upper soil layers and the original profile is changed only slightly.

With increasing slope, profiles in lands terraced by cut-and-fill techniques are increasingly altered, both on the cut and the fill side of the terrace. Table 1 shows the maximum cut and fill as related to slope for various terrace widths. Deep cuts and fills, which would be required for making wide terraces on steep slopes, are rarely made and terrace width tends to decrease rapidly with slope increase.

The effect of changes of the soil by cut and fill depends to a large extent on the original soil profile. On nonlayered soils of a more or less uniform texture, little permanent effect will be noticeable. Even though the plow layer disappears from the cut part and is increased in thickness in the fill part, a new surface horizon (Ap) will form. Therefore, the disturbance of the surface horizon

Table 1. Maximum cut and fill for different terrace widths.[a]

Original slope (%)	Maximum cut and fill (cm) for			
	40-m terrace	20-m terrace	10-m terrace	5-m terrace
1	20	10	ns	ns
2	40	20	10	ns
3	100	50	25	12.5
10	na	100	50	25
20	na	na	100	50
50	na	na	250	100
100	na	na	na	250

[a]ns: insignificant cut or fill to influence the profile. na: terraces not known to occur.

is hardly noticeable in older terraced paddy lands. Immediately after grading of new terraces on homogeneous soils some differentiation in rice growth may be noticed, but such a growth gradient tends to disappear in time.

Leveling in paddy terraces on soils with a strong layering—hardpan at shallow depth, horizons of strongly contrasting particle-size distribution, laterite formations, or relatively unweathered formations—may have a more lasting effect. Poor rice growth occurs where such layers are exposed or are present immediately below the plow layer. The soils within a single field become heterogeneous as a result. Heterogeneous terraced fields are not widespread because most terracing for rice in Asia has been done on relatively deep, homogeneous soils.

More fundamental changes occur when the soil material for terracing is brought from elsewhere, as in the Banaue terraces in northern Luzon, Philippines (van Breemen et al., 1970). There, soil material is eroded artificially from higher on the slope into basins preformed with a stone or earthen retaining wall at the low side of the future terrace (Fig. 3). Coarser subsoil materials are flushed in first, while the topmost layers are mainly the homogeneous, humus-containing surface layers. In such terraces the original soil profile is in no way involved in the present profile. Such soils are artificial; they are permanently waterlogged to enhance the stability of the terraces.

Landslides occur in areas with terraces on steep slopes, sometimes involving the collapse of two or more adjacent terraces. Restoration follows, often by enlarging an adjacent lower terrace at the expense of the damaged field. New soils is brought in as in Banaue, or the soil of the new terrace may be the deep subsoil of the original profile, as in restored terraces on steep volcanic slopes in Java.

Long-term changes in soil physical characteristics

Seasonal cycle of puddling and drying undoubtedly influence the structure of the surface horizon, but little seems to be known about specific long-term

3. Man-made soils of the Ifugao rice terraces, Philippines. Coarse material eroded artificially from higher on the slope is flushed into the future terrace as subsoil fill. (Photo by H.C. Conklin, Yale University)

effects of puddling on soil structure. In general, the upper 10–20 cm of the profile tends to acquire physical characteristics unfavorable for the growth of dryland crops, as exemplified by massive or blocky and platy structures (Dei and Maeda, 1973).

The development of soil structure in the subsoil after empoldering and drainage of sea and lake bottom sediments *(ripening)* has been described in seasonally well-drained, fine and very fine clayey soils used for rice in Japan (Motomura et al., 1970). Ripening is more rapid in perennially well-drained soils than in the seasonally flooded soils such as in paddy fields. However, even in paddy fields the development of prismatic structures and associated vertical fissures during ripening leads to an increase in permeability of the clayey subsoil. In recent coastal marshes of the tropics, which in contrast to nonvegetated sea bottom sediments are normally permeable in their virgin state, permeability tends to decrease after such areas are developed for paddy fields. The soil layers between 20 and 50 cm deep lose their permeability mainly due 10 collapse of biopores (Scheltema, 1974; van Breemen, 1976).

The formation of the so-called plow pan — a compacted, 5- to 10-cm thick subsurface horizon between 10 and 10 cm depth — is common to puddled rice lands. Compared to the surface soil, a plow pan has a higher (dry) bulk density and less medium-to-large-sized pores (Leung and Lai, 1974). The pans are not the result of clay illuviation because they have neither a finer texture than the adjacent horizons nor micromorphological evidence for clay movement. Their permeability is generally lower than that of the overlying and deeper horizons.

Grant (1964) pointed out that it is difficult to understand how the action of the light plow used in traditional rice growing could form a well-developed, compacted layer. Because the pans are also found where hoes are the only implement used for soil preparation, e.g. in the terraced *sawahs* of Java. it appears that the pressure exerted by human feet — or animals where used — during tillage, transplanting, and needing can be responsible for compaction. Therefore, we propose the term *traffic pan* to replace plow pan. The wet conditions under which tillage and puddling take place probably create conditions optimal for the soil's structural collapse and compaction just under the soft puddled surface layer.

Not all flooded rice lands have a traffic pan. And a traffic pan may develop in nonflooded soils, especially if they are worked when wet. Hence, the traffic pan phenomenon cannot be used as a diagnostic criterion to separate paddy soils in a taxonomic classification.

Traffic pans may be absent or weakly developed because of external factors. For instance, where rice is direct-seeded as in the deep-water rice areas in the major river deltas of Asia and in phreatic and fluxial rice lands in Africa no (or only weakly developed) traffic pans are found because wet tillage is not customary.

Soil characteristics influence the degree of pan formation. Traffic pans do not occur, for instance, in very sandy soils, but they do appear if the silt and clay content are somewhat higher than in loamy fine sand. Optimal conditions for compaction are present in fine loamy soils (Mitsuchi, 1968). If the clay content is much higher, however, pan formation again becomes less pronounced.

Curfs (1976) found an incipient pan formation in fine sandy loams (Fluvents) in Nigeria, after as little as 3 years of mechanized wet-rice preparation. In polder lands of the Shiroishi area, Kyushu (Japan), with fine clayey sediments, no pan formation was apparent after 10–12 years of rice culture but incipient pans formed after 50 years, and well developed pans after more than 200 years (Kanno et al., 1964; Motomura et al., 1970).

In Vertisols, any incipient pan is destroyed by the cracking and self-mulching typical of those soils (see Fig. 4, Chap. 4). Poor pan formation is also found in soils with a stable structure (Andepts and Oxisols), and in soils with high organic matter contents.

For both anthraquic and irrigated rice lands on permeable soils without a natural or induced high water table, a traffic pan is important to water retention. This is especially true in soils where the puddled surface layer dries and cracks — and thus loses its low permeability — in soils where the puddled topsoil is relatively permeable because of a coarse texture or a high aggregate stability, or in soils where there is low-intensity wet tillage.

In many cases, a traffic pan makes wet land accessible for man, beast, or machine. This may be best seen in paddy fields where the traffic pan is broken. In certain soils, especially those of intermediate texture, the breaking of the traffic pan results in soils becoming muddy and nonresistant to pressure to a considerable depth. The use of tractors on such soils is seriously limited. Breaking the traffic pan by deep mechanized plowing under dryland conditions in northeast Thailand caused serious problems in trafficability in the following wet season; tractors sank to a depth of more than 50 cm, which interfered seriously with crop operations. Similar damage to the traffic pan by tractor-driven rotary tillers and subsequent loss of trafficability is reported from Malaysia (Wijewardene, 1975).

The traffic pan has a positive effect on the water economy and crop performance in most paddy lands cultivated to wetland rice: but that is not true if the same land is used for dryland crops in rotation with rice. A well-developed traffic pan creates a shallow soil that seriously interferes with root growth, and moisture and nutrient availability for dryland crops. Moreover, ponding due to unseasonal rains may adversely affect the dryland crops. The presence of traffic pans inhibits the use of the same land for both paddy rice and dryland crops.

Textural differentiation and illuviation of soil material

Profiles of soils used for wet rice cultivation often show a textural differentiation characterized by a low clay content of the surface 20–30 cm. There is no clear evidence that illuviation of clay is caused or enhanced by wet rice cultivation. For instance, although the clay content of the surface horizon seems to have decreased measurably in some rice-growing soils on recent alluvium — within 40 years (Kostenov, 1975) to 350 years (Kanno et al., 1964) — the removal of clay from the surface was not associated with a clear increase at some depth.

Additionally, there is no direct micromorphological evidence of increased illuviation, such as clay skins, in wet-cultivated rice lands. The lower clay content near the surface of many wet-cultivated soils is probably due mainly to their weathering associated with alternate flooding and drainage, as described by Brinkman (1970) who coined the term *ferrolysis* for this typical soil-forming process. Another process that can contribute to loss of clay from the surface soil is its removal in the surface water during puddling when muddy water overflows from the higher to the lower fields. An opposite process of enrichment with clay-size particles in the surface soil is sometimes brought about by irrigation with muddy water.

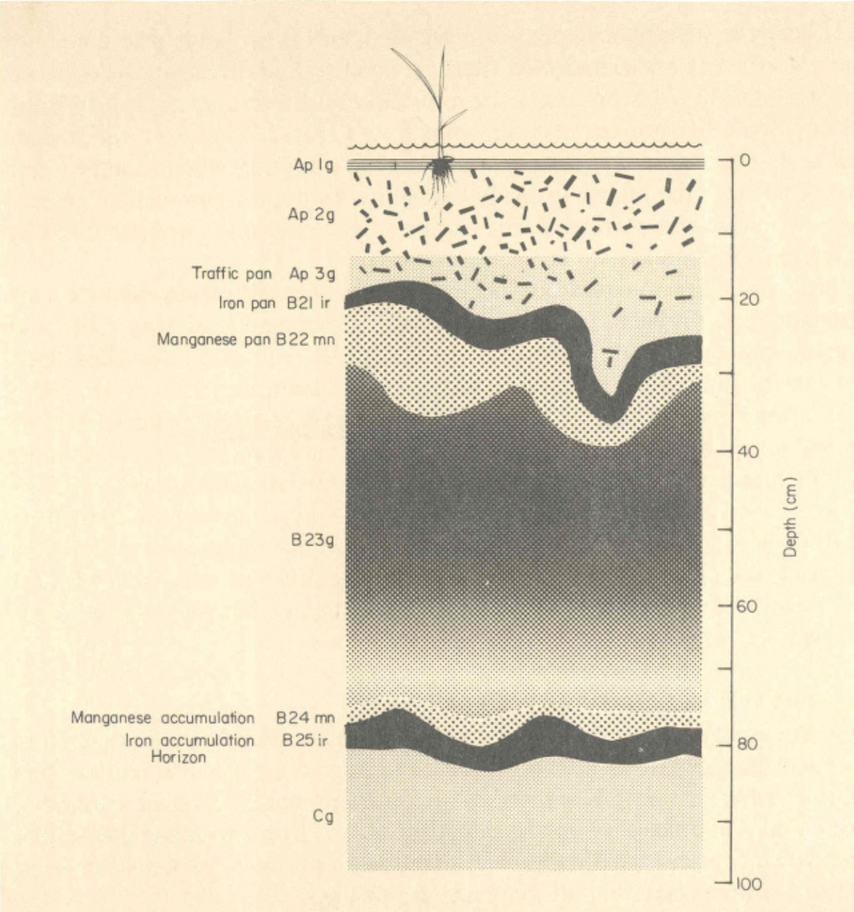
Although there is no reason to believe that net rice cultivation enhances clay illuviation, it probably promotes downward movement of clay, silt, and organic matter through cracks and pores. This is seen in the so-called flood coatings of the subsoil by surface soil material (Brammer, 1971b; Mitsuchi, 1974a; van Breemen, 1976). The coating material is believed to move from the topsoil under hydraulic pressure when the soils are flooded; coating is most prominent in deeply flooded soils and least developed in soils that are only shallowly flooded for short periods. Soil reduction — by removing the cementing qualities of iron oxide — and puddling may enhance migration of surface soil material, and flood coatings can form rapidly in cultivated soils, even within 1 or 2 years. Flood coatings also occur in seasonally flooded soils under forests and grass.

Migration of iron and manganese

Iron and manganese share one characteristic not possessed by other common chemical elements in the soil: they tend to form sparingly soluble oxides upon aeration, whereas they are reduced to the far more mobile divalent state upon reduction. This accounts for the redistribution of iron and manganese often observed in seasonally flooded soils, sometimes to the extent that distinct iron- and manganese-accumulation horizons are formed.

Following the classic study by Koenigs (1950) of a *sawah* profile near Bogor, Indonesia, which contained an indurated iron-oxide pan overlying a manganese-oxide accumulation horizon, many reports appeared of soils with clear iron- and manganese-accumulation horizons due to wet rice cultivation (Kawaguchi and Matsuo, 1957; Kanno et al., 1964). These studies gave rise to the concept of typical *paddy soils* (Dudal, 1958) or *Aquorizems* (Kyuma and Kawaguchi, 1966). However, whereas such accumulation horizons are often well-developed in originally freely drained and permeable soils on anthraquic rice lands, they are at best inconspicuous or weakly developed in most naturally hydromorphic soils found in fluxial rice lands.

Nevertheless, the modal paddy soil profile in anthraquic rice fields as depicted in Figure 4 is useful as a frame of reference when discussing migration of iron and manganese. This profile has a periodically reduced surface horizon over a traffic pan, and a permanently reduced deep subsoil. A predominantly oxidized subsurface horizon is sandwiched between them. The accumulation horizons are found just below the periodically reduced surface soil and just



4. Horizons in a so-called *Aquorizem* profile. (Modified from Grant, 1965)

above the permanently reduced subsoil. The maximum iron accumulation is always found in the soil layers adjacent to the reduced horizon, whereas the manganese accumulation is always facing the oxidized subsurface layer.

The lowest set of accumulation horizons represented in Figure 4 is related to the presence of shallow groundwater throughout the year and is lacking in deeply drained soils. Provided the subsurface horizons remains fully oxidized throughout the flooding period (the requirements for this condition are discussed later), the processes involved in the formation of such iron and manganese accumulation horizons are relatively simple. Fe^{2+} and Mn^{2+} are dissolved by soil reduction in the flooded surface soil and will also be present in the reduced zone below the permanent groundwater table. At the same time, they will be oxidized and removed from the solution at the interface of the reduced zones and the oxidized subsurface horizon. The concentration gradient thus established causes a diffusional transport from the reduced to the oxidized zones and leads to the formation of horizons of absolute accumulation. Whereas diffusional transport, and sometimes lateral mass transport (interflow), brings about the formation of the deepest accumulation horizon, vertical mass transport through percolation is most important in the formation of the upper iron-manganese horizon (Mitsuchi, 1975). Because the ferric oxides have a solubility range that is several orders of magnitude lower than 3- and 4-valent manganese oxides, and because Fe^{2+} is able to reduce such manganese oxides, iron precipitates closest to the reduced horizon and manganese migrates further into the oxidized zone.

In practically all paddy soils drained to below the rooting zone during a fallow period, the subsoil remains oxidized for some time after flooding — while reduced conditions already prevail in the surface horizon (see Fig. 2, Chap. 4). This surface gley may be due to

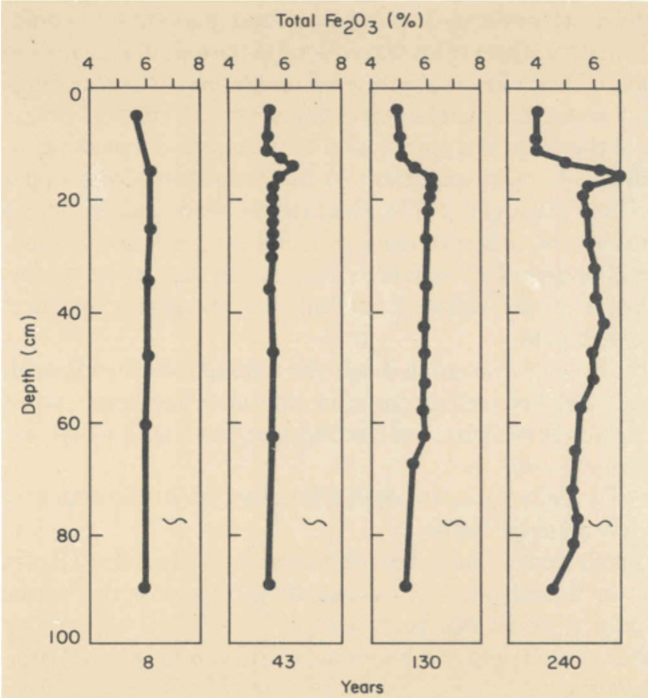
- low permeability of a traffic pan, an argillic horizon, an iron-manganese oxide pan or the soil material itself;
- entrapping of air inside peds if the soil is submerged by surface flooding (in pluvial-anthraquic or fluxial rice land) rather than by a slow rise of the groundwater (in most phreatic rice lands); or
- a low organic matter content and low microbial activity in the subsoil compared to the surface soil.

These factors all lead to subsoil accumulation of iron and manganese oxides at least during the early part of the flooding period. After several weeks of submergence, reduced conditions that may develop in the subsoil of naturally aquatic lands lead to at least partial dissolution of the iron and manganese formed earlier. But due to trapping of Fe^{2+} and Mn^{2+} by the cation exchange complex, part of the translocated iron and manganese will be retained in the subsoil (Wada and Matsumoto, 1973) and oxidized the following dry season.

In many naturally hydromorphic soils the subsurface iron and manganese accumulation appears only as a slight bulge when plotting the analyzed free iron content against depth, and can be distinguished morphologically, at most, as a zone showing a somewhat stronger brown mottling. Strongly developed accumulation horizons are confined to anthraquic soils with

- a deep groundwater table and a slowly permeable subsurface horizon, factors that promote the maintenance of oxidized subsoil conditions and at the same time allow some percolation; and
- a low pH, a high content of easily reducible iron oxide, and sufficient well-decomposable organic matter in the surface soil, which promote the development of high concentrations of Fe^{2+} and Mn^{2+} in the soil solution.

Some of the best known examples of iron-manganese accumulation horizons come from two completely different soils — terraced Rhodic Paleudults from volcanic parent material in Java (Koenigs, 1950) and Haplaquepts in relatively recent polders (10–450 years old) in Japan (Fig. 5). In favorable conditions a



5. Distribution of iron oxides (Fe_2O_3) with depth in anthraquic rice fields in polders of different ages. The lowest level of the groundwater is indicated by~. (After Kawaguchi and Matsuo, 1957)

detectable accumulation of iron oxides can take place in about 40 years; that of manganese oxides in as little as 8 years (Kawaguchi and Matsuo, 1957).

Reduction by organic substances in water percolating from the flooded surface can cause the formation of gray linings of the rusty channels often seen in hydromorphic subsoils (Wada and Matsumoto, 1973).

In soils developed on highly weathered parent material, as in many Ultisols in the tropics, manganese contents are normally so low that manganese-accumulation horizons cannot form (Kawaguahi and Kyuma, 1977). The relatively high mobility of manganese in acid soils may lead to the complete absence of manganese oxides, e.g. in acid sulfate soils, which often show a horizon of marked iron-accumulation but no manganese-accumulation horizon (van Breemen, 1976).

Laterite or plinthite layers found in rice fields in some areas are due to absolute accumulation of iron that was conveyed from elsewhere as dissolved Fe^{2+}.

Under special conditions translocation of iron and manganese due to periodic flooding can be counteracted by biological or physical homogenization of the soil profiles. For example, iron- and manganese-accumulation horizons are often weakly developed or absent in paddy soils on river levees, which are well-drained during most of the year and often have a rich soil fauna. In Vertisols the churning action associated with the swelling and shrinking of montmorillonitic clay has a similar effect.

Changes in base status and soil mineralogy under seasonal flooding

There is ample evidence that the base status of soils is influenced by seasonal flooding. In some rice-growing soils, the base saturation increases after flooding, whereas in others it decreases (Mitsuchi, 1974a). Whether an enrichment or depletion takes place depends on the balance between influx of bases, mainly from irrigation, floodwater, or interflow water, and outflux of bases by leaching and surface runoff. This holds for all soils, but the soils of paddy lands with an aquatic water regime merit special attention.

Soil reduction tends to liberate large amounts of bases, which are removed if hydrological conditions are suitable. But many paddy lands are in a topographical and hydrological setting that favors supply of bases from elsewhere. Although it is often difficult to say which of these two opposing tendencies prevails, a depletion of bases will undoubtedly occur in pluvial-anthraquic rice lands as those normally found in the higher aspects of the landscape, while net gain in bases may take place in irrigated or fluxial rice land receiving sediment-loaded irrigation or floodwater.

Dissolved bases (and silica) in floodwater and interflow are often retained in the soil in areas where there is little or no excess of rainfall over evaporation. Such retention of bases will increase the exchangeable bases and may also cause formation of new minerals such as carbonates and smectites (montmorillonitic clay minerals). The formation of the readily soluble sodium bicarbonate and carbonate minerals in highly alkaline soils in arid and semiarid regions is an extreme example of this kind of enrichment. Reclamation of such soils for wetland rice cultivation, however, may induce a net loss of bases due to the percolation and runoff that accompany flooding in most cases.

Biological fixation of calcium bicarbonate from irrigation or interflow water by mollusks living in rice fields and irrigation canals was observed in several lowland areas in the Philippines. At the International Rice Research Institute 15 years of intensive irrigation with bicarbonate-rich water high in Na^+ (90 ppm) and Mg^{2+} (20 ppm) has resulted in a pH increase of 5.5–6.0 to 6.5–7, indicating that some soil acidity has been neutralized by the bases in the irrigation water. At the same time, large amounts of mollusks shells are present on the soil surface and in irrigation water reservoirs indicating that appreciable amounts of calcium carbonate have accumulated.

The opposite process, decalcification due to seasonal flooding, has been described in the calcareous Ganges and Meghna sediments in Bangladesh. There, flooding is mainly with rainwater and the content of bases of the floodwater is low. At the same time, the production and accumulation of carbon dioxide in reduced surface soils dissolve part of the calcium carbonate present. The resulting calcium bicarbonate in the soil solution is removed by lateral drainage or percolation. The rate of decalcification is rapid compared to that in dryland soils. Losses of about 2% calcium carbonate in 25 years are reported in young Ganges sediments that had 5–10% calcium carbonate at the time of their deposit (Brammer, 1971a).

Other minerals also tend to weather more rapidly in soils flooded seasonally with water low in bases. That may ultimately lead to paddy soils with a strikingly low clay content, a low pH, and a low base saturation near the surface. These so-called *degraded* paddy soils are also depleted in iron and manganese oxides and in organic matter.

Strong weathering under seasonal flooding is attributed to a specific hydromorphic-soil-forming process that Brinkman (1970) named *ferrolysis.* Ferrolysis consists of displacement of exchangeable bases by dissolved ferrous iron produced during soil reduction, removal of the displaced bases by leaching or runoff, and oxidation of adsorbed ferrous iron to ferric oxide and exchangeable hydrogen during the following dry season. Hydrogen-saturated clay is unstable and will partly decompose to give aluminum-saturated clay and silica. Repeated cycles of reduction plus leaching followed by oxidation may lead to a rapid decrease in base saturation and also to a rapid removal of weatherable minerals.

Clay minerals with a high layer charge, such as smectite, illite, and vermiculite, are particularly vulnerable to ferrolysis. Kaolinite is destroyed more slowly partly because of its lower cation-exchange capacity. The decrease in pH accompanying ferrolysis helps to explain the remarkably rapid rate of weathering of biotite in some periodically reduced surface horizons of soils in recent floodplains and on older river terraces (Huizing. 1971). Ferrolysis is counteracted or masked in soils rich in easily weatherable minerals (e.g. calcium carbonate) or in soils receiving ample amounts of bases with flood or interflow water. The bases delivered by the minerals or supplied from elsewhere not only compete with ferrous iron at the exchange complex during flooding, but also neutralize any acidity developed during a following dry period.

The effects of ferrolysis are expressed most clearly in soils derived from acidic rocks, or in soils formed on old sediments with low contents of easily weatherable minerals where flooding is mainly by impounding rainwater. But incipient ferrolysis seems to also play an important role in many noncalcareous soils on young and semirecent alluvial sediments. This is strongly suggested by comparing the low pH and low base saturation of the surface soil to that of the subsoil in most lowland soils in Southeast Asia. For esample, 107 paddy soils (not including calcareous Vertisols and acid sulfate soils) from widely separated parts of Thailand had a surface-soil pH that averaged about half a unit lower than the subsurface horizon (Kawaguchi and Kyuma, 1969b, unpublished data, Land Development Department, Thailand). In contrast, most dryland soils in monsoonal areas have a slightly higher pH at the surface than in the subsurface horizon.

Ferrolyzed soils are poorly productive in an advanced stage of development. They are low in nutrients because of their low cation-exchange capacity and low organic-matter content. Those two properties, together with an often silty or sandy surface soil, also account for a low water-holding capacity. In Japan, rice grown on degraded soils frequently suffers from hydrogen-sulfide toxicity after fertilization with ammonium sulfate.

A process related to ferrolysis appears to be responsible for the strong acidification of the surface horizon of periodically flooded, young marine sediments. During flooding sulfate salts and ferric oxide are reduced to immobile ferrous sulfide and dissolved bases. The latter are partially removed by runoff. In the dry season, the ferrous sulfide is oxidized to ferric hydroxide and sulfuric acid, which explains the common occurrence of low topsoil pH in young soils.

An opposite process, deacidification, takes place in the periodically flooded topsoils of acid sulfate soils where the pH in the root zone of initially very acid soils tends to stabilize at a value between 4.5 and 5. The ultimate result is that such soils used for wetland rice growing tend to reach the same pH range in the dry surface soil, irrespective of the initial soil pH, after acidification (van Breemen, 1975).

The clay mineralogy of acid soils in use for aquatic rice growing is subject to changes due to the formation of soil chlorite (Brinkman, 1970; Mitsuchi, 1974b). In the surface horizons of such soils, exchangeable aluminum is neutralized during reduction of ferric oxide. As a result any 2:1 clay minerals present become interlayered with aluminum hydroxide leading to the formation of 2:2 *soil chlorite.* The aluminum hydroxide interlayer will trap some previously exchangeable cations and will also neutralize part of the negative charge of the clay, leading to a progressively lower cation-exchange capacity. This process is often found in soils undergoing ferrolysis.

Changes in the organic matter fraction

Rice is grown on soils that vary widely in organic matter content. Kawaguchi and Kyuma (1974a) found large differences in total organic carbon in paddy soils of tropical Asia, the Mediterranean countries, and Japan (Table 2).

Natural variation in organic matter content and quantitative and qualitative differences in the humus of aquatic rice lands, as compared with those of adjacent nonflooded lands, depend on several factors. Differences are related mainly to climate, hydrologic conditions, soil-forming processes, and soil mineralogy.

CLIMATE. Lowest organic carbon contents are found in the soils in areas characterized by relatively low annual rainfall and high temperatures at some time of

Table 2. Organic carbon contents (in % of air-dry soils) in the surface horizon of lowland paddy soils.[a]

Region	Samples (no.)	Organic carbon contents (in % of air-dry soils)			
		Mean	Standard deviation	Minimum	Maximum
Tropical Asia	410	1.4	1.3	0.12	11.4
Mediterranean	62	1.8	1.5	0.35	8.6
Japan	84	3.3	2.0	1.00	11.4

[a] Source: Kawaguchi and Kyuma, 1974a.

the year. Organic carbon contents are relatively low in soils in most of India; in drier zones of other tropical Asian countries, such as northeastern Thailand, Cambodia; and in the dry zone of Sri Lanka.

Within comparable tropical temperature zones, the organic matter content of pluvial rice lands tends to be inversely related to the length of the dry season. The highest values are in soils of areas without or with only a short dry season. For aquatic rice lands not continuously wet, a similar relationship was found by Kawaguchi and Kyuma (1974a).

Of the three areas sampled (Table 2) organic matter is highest in Japan. This may be mainly because there the temperatures are lowest, but the presence of allophane in Japanese soils may have also contributed to high organic carbon. The decrease in temperature with increasing elevation explains why the organic matter content in soils on pluvial rice lands generally increases with elevation.

HYDROLOGY. Seasonal flooding and drainage often appreciably influence the content and properties of humus, which is the more or less stable portion of soil organic matter. Several authors report an increase in organic-matter content attributable to wet rice cultivation (Kang Sek Hjon and Markert, 1959; Raymundo et al., 1962; Kanno et al., 1964: Mitsuchi, 1974a), but others report lower organic carbon in paddy soils than in comparable adjacent soils under forest or dryland crops (Karmanov, 1966; Kostenov, 1975). Seasonal flooding seems to enhance development of humus that is generally more poorly humified, higher in fulvic acid, and less tied up in the clay-humus complex (Harada et al., 1955; Mitsuchi, 1974a; Kostenov, 1975).

Factors that tend to be responsible for an increase of organic carbon in wetland paddy soils are

- the lower rate of decomposition of fresh plant material in anaerobic than in aerobic soil, and
- the heavy application of organic manure and compost on rice land, at least in China, Korea, and (formerly) Japan.

But sometimes factors that tend to lower the organic matter content are dominant.

- Alternate wetting and drying or flooding and drainage stimulate microbial activity and cause strong decomposition of organic matter (Kato, 1972).
- In ferrolyzed (degraded) paddy soils the low base status hampers humification and is partly responsible for the more mobile character of organic matter in such soils.
- Dissolved organic matter (mainly polyphenolic compounds) attains a higher concentration in anærobic than in ærobic soil, especially if the soil is poor in easily reducible ferric oxides (Wada et al., 1975); therefore removal of organic matter by leaching can be appreciable, especially in ferrolyzed soils.
- In young soils regularly flooded by silt-loaded river water (Fluvents), organic matter in the surface soil is continually diluted with mineral soil material.

The first three mechanisms for removal of organic matter are most important in poor, coarse-textured soils that are low in free iron oxide and show appreciable percolation of water, and in pluvial-anthraquic soils with irregular shallow flooding.

Otherwise the hydrological factors that promote an increase in organic matter predominate in most rice lands. For instance, within a given toposequence the more hydromorphic soils in the lower positions have a higher humus content than the soils of the higher, better-drained parts. This influence of hydrological conditions can clearly be demonstrated on many river plains where the higher, better-drained rice fields on, or adjacent to, river levees have a lower organic matter content than those in the basins or backswamps.

In the lowest topographic positions, transitions from mineral soils to organic soils (Histosols) occur. Backswamps or basins in monsoonal climates with a pronounced dry season have less organic soils in the low-lying parts of rice-growing areas. The presence of organic soils (Histosols, histic subgroups) is, therefore, indirectly related to climate, with the most extensive peat areas occurring in the udic and perudic zones of tropical Southeast Asia (Andriesse, 1974; Soepraptohardjo and Driessen, 1976).

MINERALOGY. Humification is promoted in soils developed from basic parent materials that have not undergone extreme weathering. For instance, the Tropohumults, Alfisols, and Mollisols developed from basic volcanic material have a markedly higher humus content than soils from more acidic rocks developed under a comparable environment.

Another mineralogical factor of importance in volcanic regions is the allophane content in Andepts. Due to interaction between the amorphous mineral soil constituents and organic matter, humus contents are generally high in the presence of allophane, although that may be less so under wet rice cultivation than under dryland conditions (Mitsuchi, 1974a).

The wide variability of humus content in rice-growing soils is thus related to a multitude of factors, which often interact. Moreover, soil management can change these values considerably, causing differences to occur from field to field, and even within a field.

SOIL CLASSIFICATION ASPECTS OF PERMANENT CHANGES

In the preface of *Soil taxonomy* is the statement, "no proposals have yet been developed for classifying soils that have been altered by flooding for rice and taro." While we do not make firm proposals here, we try to consider some implications of the changes in flooded rice-growing soils.

Light and frequently temporary changes of the surface soil — common in many paddy soils on coarse-textured materials and also in self-mulching Vertisols used for aquatic rice land — can be accommodated, if at all, only at the lowest levels of the taxonomic classification — the *series* level. For soil survey purposes, such slight changes can be indicated as a specific land-use *phase* of an established mapping unit.

As detailed in the previous section, major permanent profile changes occur in soils on many aquatic rice lands. Often, these changes can be accommodated in the existing classification system, and an appropriate taxon found. This, for instance, is the case with soils changed in the process of terracing. Even where the profile is completely renewed, such as described for the Banaue terraces of the Philippines, an appropriate taxon can be found. In that case, the original profile may have been an Udult but in the terrace it has become an Aquent and should be classified as such. More frequently, the effect of terracing is less pronounced, and the new characteristics acquired can be recognized at a lower level in the classification. In relatively few cases, the changes due to terracing of moderate to steep slopes require recognition at a level higher than the subgroup. Terracing, however, poses a problem to the field soil scientists because soil areas that could be characterized under natural condition by one or a few soil classification units distributed in a regular pattern now become heterogeneous with in-field variations that are difficult or impossible to map separately. Terraced areas that have acquired such soil microvariability should be indicated separately as complex units on soil maps.

Two other kinds of changes that can affect the classification of soils in aquatic rice fields are changes in moisture regime and changes due to formation of additional horizons.

Changes in soil moisture regime

In *Soil taxonomy* the soil moisture regime is an important soil property and is cited as a determinant of processes that affect the morphology of the soil. The aquic moisture regime implies a reducing regime that is virtually free of dissolved oxygen. For differentiation at the suborder level, the whole soil must be water saturated at least periodically, while at the subgroup level only the lower horizons are saturated.

The moisture regime of soils that are continuously saturated at or near the surface is called peraquic. To be recognized in the classification, the effects of an aquic moisture regime must be measurable in terms of the presence of grayish or bluish colors with a low chroma either of the whole soil mass, or occurring as mottles. The duration of the period that a soil must be water saturated to qualify for an aquic moisture regime is not known. It should be long enough for the removal of dissolved oxygen, which usually takes only a few days for surface soils containing decomposable organic matter.

The effect of impounding water in rice fields is generally an increase in soil wetness. In the case of well-drained soil, the soil moisture regime may become aquic but in imperfectly or poorly drained soils, the aquic moisture regime may be reinforced. The degree of change of the moisture regime and the degree to which this change results in modification of the soil morphology depends on the nature of the original soil, as well as the soil and water management.

There is no easy way to distinguish these induced aquic suborders from soils that have a naturally aquic moisture regime. Careful long-term monitoring of the degree of water saturation of the different soil horizons may reveal that water saturation takes place from the top down, and simultaneously from a rising water table. This is contrary to what is normally found in naturally wet soils, but the specific dynamics of water saturation is not a diagnostic characteristic per se in *Soil taxonomy.* When drained and no longer in use far rice, such soils tend to revert to their natural status. There are, however, few indications as to how long it takes for a soil to revert.

The use of well- or moderately well-drained soils of the fine loamy to clayey families for ponded rice growing may cause the development of superficial gleyed horizons that meet the requirement of *Soil taxonomy* for soils with an aquic moisture regime. Low-chroma mottling or matrix colors develop in the Ap and also in the underlying horizons, more particularly in the dense traffic pan often present in such soils. In many cases, the low-chroma mottling is found below the traffic pan to a depth of 40–50 cm. Below the gleyed superficial horizons, the soil horizons retain their original colors, and gray mottles or matrix colors are absent, indicating that no recurrent reductive conditions are present. A groundwater gley horizon is often present at greater depth, but the surface and groundwater gley horizons are separated.

The classification of soils belonging to aquic suborders with low-chroma mottling throughout the profile does not normally change because of long-term ponded conditions. However, there may be changes in morphology not reflected in the classification.

In paddy fields submerged for long periods, the subsurface horizons may develop neutral gray colors due to continuous waterlogging and absence of oxygen (see Fig. 2, Chap. 4). This is seen in double- and triple-cropped, irrigated rice land on fine clayey Inceptisols, but the phenomenon is not widespread. Such soils may lose the characteristics required to classify them as Inceptisols particularly the cambic horizon, and they may become Aquents.

A change at the suborder level due to ponding is known to occur in Vertisols. Usterts, characterized by cracks that are open 90 cumulative days in most years, will lose this diagnostic characteristic, and will become Uderts. This change occurs locally in Vertisols in valley bottoms that are used for double-cropping of rice under irrigation.

Ponding of water usually leads to the development of aquic characteristics in the surface and subsurface horizons. Where these induced aquic morphological characteristics form a continuum with deeper horizons that have the properties of a natural aquic moisture regime, the classification according to *Soil taxonomy* may change profoundly. Soils that in their natural status would belong to an aquic subgroup can shift to an aquic suborder under sustained paddy cultivation where water is impounded during sufficiently long periods each year. Orders in which such a transfer to the aquic suborder is most common are Inceptisols, Alfisols, and Ultisols. Such land use-induced Aquepts, Aqualfs, Aquults, and others belong, with few exceptions. to clayey families with a low hydraulic conductivity and a restricted downward movement of the water (Mitsuchi, 1974a, 1975).

The development of inverted gley has been described by various authors (Koenigs, 1950; Kanno, 1956; Kyuma and Kawaguchi. 1966; Moormann and Dudal, 1968; Mitsuchi, 1975). The expression differs according to the original soil conditions and is related to the type of water management. It is most strongly developed in soils that were originally relatively acid and subjected to continuous ponding for longer periods, i.e. in udic climates and with irrigation.

The development of a surface and subsurface gley, diagnostic of a superficial aquic moisture regime, should be recognized in a taxonomic classification. This can be done by introducing *anthraquic*[1] (from anthropic, i.e. man-induced and aquic, indicating the specific moisture regime) subgroups of the taxa at a higher categorical level. An anthraquic soil moisture regime can be defined as periodic man-induced water saturation, and reduction of the soil to a depth of at least 40 cm, without a corresponding periodic water saturation in the horizon below. The morphology of anthraquic subgroups is characterized by low chroma colors in the superficial horizons to a depth of 40 cm or more - the colors to be defined according to the definitions of the aquic suborders in *Soil taxonomy.* To differentiate anthraquic subgroups from aquic suborders, the anthraquic soils should have higher chromas below the superficial gley horizons, with or without rusty mottles present.

Changes in taxonomic classification due to recurrent inundation in paddy fields mill occur in such taxa defined as sodic soils and those characterized by the presence of a salic horizon. Reclamation of these soils and their persistent

[1] The term *anthraquic* is used in two contexts in this book. In Chapter 2, anthraquic pertains to a modification of the natural water regime. In this section, the use is more specific to such measurable changes in soil morphology as can be induced by artificial flooding and ponding of surface water.

use for irrigated paddy fields may lead to disappearance of the diagnostic horizons, which are rich in soluble salts. The great groups involved are Salorthids and Halaquepts.

Changes due to the formation of additional horizons

As described earlier, leaching of iron and manganese from the reduced surface horizons and subsequent accumulation of ferric oxides and manganese oxides take place in the soils of certain anthraquic rice fields.

Usually the iron-manganese accumulation horizon is weakly expressed and cannot serve as a diagnostic subsurface horizon in the sense of *Soil taxonomy.* However, under certain conditions, a distinct accumulation horizon of iron or iron-manganese may be formed. Examples are those described by Koenigs (1950) for the sawah profile in Udults near Bogor, Indonesia, and by many authors elsewhere in Asia. Where this situation arises, a provision should be made to recognize the new horizons at an appropriate level in *Soil taxonomy.* Often, the iron oxide accumulation is indurated. *Soil taxonomy* makes a provision for the classification of thin iron pans or placic horizons, most of which, however, are formed under rather different conditions. Placic great groups and subgroups have been introduced and it is feasible to use this terminology, probably in conjunction with anthraquic, at the subgroup level of the taxa involved. For distinct horizons of iron or iron and manganese accumulation that are not indurated like placic horizons, the term *hydroferric* might be proposed. The degree of accumulation, however, remains to be specified before firm recommendations for the introduction of *hydroferric* taxa at the subgroup level can be made.

It should be noted that the two proposed accumulation subgroups correspond reasonably well with the *Aquorizem* unit of Kyuma and Kawaguchi (1966). However, we do not favor elevation of the *hydroferric* segment beyond the level of the subgroup, while the placic segment may be recognized at either the great group or the subgroup level, preferably the latter.

Another change in horizonation in soils of paddy fields can be caused by ferrolysis, described earlier. In its advanced form, ferrolysis leads to the formation of an albic horizon, often accompanied by tonguing and interfingering of albic material in the underlying horizon. Ferrolysis is not exclusive to paddy soils, but the formation of *surface water gley soils* showing the effects of the process is strongly enhanced in puddled paddy lands in which traffic pan has developed (Brammer and Brinkman, 1977). The formation of an albic horizon paired with a net loss of clay from the surface horizon is most pronounced in acid paddy soils (frequently Aquults) on older sedimentary formations.

As Brinkman (1977) pointed out the classification according to *Soil taxonomy* of the surface-water gley soils with a distinct albic horizon presents difficulties. While certain of these soils fall under existing taxa (e.g. Albaqualf, Albaquult, Glossaqualf), others do not. A case in question is certain soils in Bangladesh where the net loss in clay due to clay destruction and the formation of an albic horizon do not correspond with an underlying clay-enriched argillic horizon. Recognition of a great group *Albaquepts* would provide a place for these soils. However, more extensive taxonomic studies of soils subject to ferrolysis must be made to define the diagnostic criteria that can separate them into distinct taxa.

CHAPTER 6

Soil and land properties that affect the growth of rice

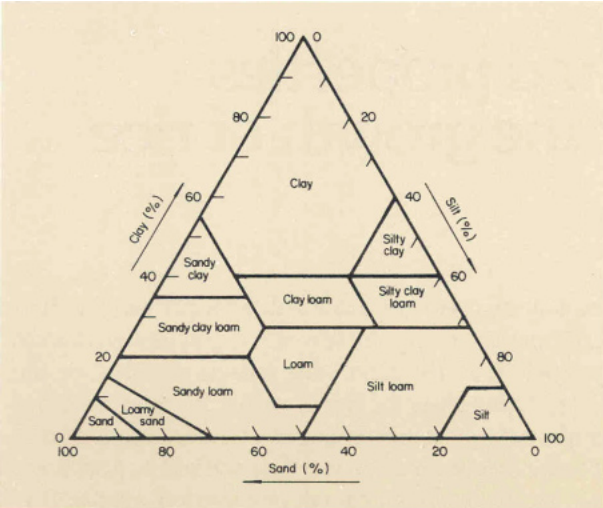
IN THIS CHAPTER, we discuss a number of reasonably stable properties of soils in relation to growth and performance of rice. Because it is impossible to discuss all such properties in detail, we made a selection that reflects our ideas on the importance of the inherent soil properties for rice growing. Because we chose only reasonably stable properties, the nutrient status of surface soils is discussed only in relation to some inherent soil properties, and not as a separate property. Nutrient status is important, but it cannot be considered as *reasonably stable* because often the use of fertilizers changes it readily.

Of the properties discussed, texture and mineralogy are used in *Soil taxonomy* (USDA, 1975) as family differentials for mineral soils. Within the morphogenetic taxa distinguished at a higher level those two and other properties discussed here have the most important effects on soil responses to management. Therefore, this chapter is a natural and, managementwise, important sequel to Chapter 5.

In addition to soil properties, we discuss several land properties where soil *per se,* although important, is not the major factor in the relationship between environment and rice growth. Specifically this is true in the relationships between upwelling of groundwater and certain problems encountered in rice growing. For salinity and alkalinity we must treat climatic and hydrological aspects in addition to the properties of the soils involved.

TEXTURE

Particle-size classes refer to the grain size distribution of the whole soil. Texture refers to the fine-earth fraction (particles of less than 2 mm) diameter and is determined by the relative proportion of clay fraction less than 0.002 mm). silt (0.002–0.05 mm), and sand (0.05–2 mm) (USDA, 1975). Soil taxonomy uses particle-size classes to define the longer categories of soil classification, i.e. soil families and soil series. Textural classes that do not specify material coarser than 2 mm are more generally used for profile descriptions. Figure 1 graphically represents textural classes. The main particle-size classes of soils used for rice growing are those with less than 35% (by volume) of particles coarser than 2 mm. There are four such classes, distinguished by texture (all percentages are mass fractions of the fine earth).



1. Weight percentages of clay (fraction smaller than 0.002 mm): silt (0.002 to 0.05 mm), and sand (0.05 to 2.0mm) in the basic soil textural classes (after USDA, 1975).

1. *Sandy.* The texture of the fine-earth fraction is sand or loamy sand but not loamy very fine sand or very fine sand.

2. *Loamy.* The texture of the fine-earth fraction is loamy very fine sand, very fine sand (dominant fraction between 0.05 and 1 mm), or finer, with less than 35% clay. Coarse loamy is defined as having less than 18% clay, while fine loamy has 18–35% clay.

3. *Silty.* This material has less than 35% clay, less than 15% fine or coarse sand, or both. Coarse silty material has less than 18% clay and fine silty has 18–35% clay but no coarse silty soils are known to be grown to rice.

4. *Clayey.* The fine earth fraction contains more than 35% clay. This particle size class is subdivided into fine clayey (35–60% clay) and very fine clayey (60% clay or more).

Materials having more than 35% by volume of coarser fragments (from 2 mm to 7.5 cm) are called fragmental when there is not enough fine earth to fill the interstices between the coarse fragments, and sandy-skeletal, loamy-skeletal, or clayey-skeletal when the fine earth fraction fills the interstices. The coarse-particle size classes occur only sporadically in soils used for rice. No rice growing has been reported on soils that are fragmental or sandy-skeletal at the surface or at shallow depths (within 50 cm). Strongly contrasting classes of particle size within the upper parts (variable) of soil profiles can be indicated by a double name, e.g. sandy over clayey, or loamy-skeletal over sandy.

Table 1. Distribution of particle-size classes of surface soils of aquatic rice lands in tropical Asia (adapted from Kawaguchi and Kyuma, 1974b).

	Frequency (%) of particle-size class[a]					
	Sandy	Coarse loamy	Fine loamy	Fine Silty	Fine clayey	Very fine clayey
Bangladesh	0	6	46	19	21	0
India	0	4	39	2	32	23
Indonesia	0	2	26	2	38	32
Malaysia	3	3	23	0	56	15
Philippines	0	4	31	2	35	28
Sri Lanka	7	27	40	0	23	3
Thailand	4	21	28	1	12	33

[a]No samples with a coarse, silty particle-size were found.

Texture of soils on which rice is grown

Rice is grown on soils of widely varying particle-size classes, but most such soils have a medium (fine loamy) to fine (fine clayey) particle-size distribution in their surface horizon. Table 1 summarizes the findings of Kawaguchi and Kyuma (1969a,b, 1974b) on the granulometric composition of 378 surface soils of aquatic rice lands in tropical Asia. Because the original Japanese textural classes have been recalculated in USDA particle-size classes, the data may contain slight errors.

A breakdown of the 378 samples according to landforms shows that fine-loamy to fine-clayey materials dominate in the young alluvial plains. Coarse soils have high frequency in (northeast) Thailand because most soils of the paddies are formed on sandy sediments derived predominantly from sandstones in the catchment area and because most surface soils have lost much of their clay due to pedogenetic processes; subsoils in the area are generally much more clayey.

In Sri Lanka, coarse-sand contents are high and silt contents are low because most alluvial material in the predominantly narrow, rice-growing inland valleys originated from weathering of siliceous crystalline rocks such as gneisses.

The Sri Lankan pattern is also seen in West African rice-growing areas where large alluvial plains are rare and where siliceous crystalline rocks (granites, gneisses) and sandstones dominate the catchment areas. Most rice-growing inland-valley soils in Sierra Leone and adjacent countries are composed mainly of sandy- to coarse-loamy materials, while the more clayey particle-size classes are found almost exclusively on the wider floodplains of major rivers and along the coast.

Soil texture in pluvial rice lands varies widely depending on the parent material and the degree of soil development. Soils derived from basic rocks are mostly clayey throughout, while soils from intermediate rocks are mainly coarse loamy near the surface and fine loamy to fine clayey in the subsoil. Relatively little rice land is found on the coarse-textured soils of the sandy or gravelly (skeletal) soil families, partly because coarse-textured soils are not widespread in the climatic areas suited for rice, but mainly because the capability of such soils for rice production is low.

Texture and performance of the rice crop

Texture, particularly textural profile, is a key factor regarding the suitability of land for rice. Various land qualities such as water regime, nutrient status and dynamics, and workability under wet and dry conditions are closely linked with soil texture.

Most studies on the relationship between texture and rice production show sandy soils as less productive than finer-textured soils. Soils with profiles in the sandy and coarse loamy particle-size classes produce satisfactory rice yields only where neither water nor nutrients are limiting. Moreover, more water and nutrients, especially nitrogen, are needed for a crop on sandy or coarse-loamy soils than on finer-textured soils in otherwise similar environments. The coarser soils thus require higher levels of management and make rice production more costly.

Rice yields on the soils of northeast Thailand are considerably below those on Thailand's more clayey rice soils, given a similar water regime and a similar (low) level of management. Likewise, the productivity of sandy paddy soils in Kyushu is lower than on the finer-textured soils in Japan.

Experimental results by Curfs (1976) on recently established Nigerian paddy fields with different textures are summarized in Table 2. With complete water control, yields on loamy sand were distinctly lower than on the finer-textured soils, but mere still relatively high because the paddies had been recently established. The response to nitrogen is clearly higher on the sandier soils.

Where water control is not optimal, the productivity of soils with a coarse texture throughout the profile is even lower. Rice can be grown successfully on soils of sandy and coarse loamy families if there is sufficient water from interflow or surface flow; but when such soils are well drained, available water is so low that they are rarely used for pluvial rice even in high-rainfall zones.

The negative effects of coarse textures in the surface soil are diminished when the subsurface horizons have a finer texture. This is commonly the case in so-called sandy rice-growing soils. With such conditions, the textural profile

Table 2. Yields of IR20 (t/ha) on soils of different textures at the International Institute of Tropical Agriculture (av. of four crops), Ibadan, Nigeria (Curfs, 1976).

Treatment	Yield (t/ha)		
	Sandy clay loam	Sandy loam	Loamy sand
No N applied	4.3	3.8	2.9
80 kg N/ha	5.2	5.0	4.0

rather than the surface soils texture determines the capability of the soil for rice production.

Although soils with a fine texture in the profile are generally superior, no consensus exists on the optimum composition for rice growing soils. This is understandable because in soils with a sufficiently high clay content, other parameters such as clay mineralogy or nutrient status assume an important role. Highest yields are from soils with 25 to 50% clay in the surface soil and a similar or somewhat higher percentage in the subsoil (Grant, 1964; Moormann and Dudal, 1968; Higgins, 1964). The data of Kawaguchi and Kyuma (1974b) indicate such a surface soil texture for about 50 to 55% of the soils of aquatic rice lands in tropical Asia. About 35% have finer texture, and the remainder have coarser texture. No data are provided for subsurface textures.

Rice yields on the very fine-textured soils are not necessarily lower. In fact, many of the best rice fields have a finer surface soil texture than that considered optimum. High clay contents, however, have several disadvantages. Very fine-textured clayey soils may crack considerably as in many of the Vertisols. Cracking interferes with land preparation and requires more water for wet tillage. Low hydraulic conductivity due to very fine textures may lead to moisture stress of rice during periods of low water supply. While enough available water may remain in the interior of structural clods of those clay soils, it is too slowly available to adequately supply the rice roots. The overall effect of the very fine textures in such soils in that while they are not ideal for rice, yields may be high when water control is perfect.

SOIL MINERALOGY AND PARENT MATERIAL

Soil mineralogy is one of the most important determinants of the inherent capability of rice soils. Considered on a regional scale, differentiation of soil quality according to mineralogy is relatively clear when rice is grown with little or no added plant nutrients, or at a low level of management. At a high level of management and with increasingly improved water control, the influence of mineralogy is harder to evaluate even though — with similar management — performance is better on soils with a more favorable mineralogy.

As an example of measured regional differences in crop performance, related mainly to soil mineralogy, data from De Datta et al. (1976) are included in Table 3. The field experiments in Laguna were on Vertic Tropaquepts and Aquolls derived from water-deposited pyroclastic (volcanic) materials. Such soils are high in weatherable minerals and have a dominance of 2:1 lattice clay minerals and allophane. The experiments in Nueva Ecija were mainly on Tropaquepts derived from recent and semirecent river sediments originating from catchment areas, where at least part of the soils are moderately to strongly weathered Ultisols. Thus, the mineralogical composition of the Nueva Ecija soils was less favorable than that of the Laguna soils.

The same is seen in Japan, where even at high levels of water and fertilizer

Table 3. Average yields of field experiments in the 1975 wet season with farmers' and high levels of management. Laguna and Nueva Ecija provinces, Philippines (De Datta et. al., 1976).

Management level	Yield (t/ha)	
	Laguna	Nueva Ecija
Farmers'	3.6	3.2
High	5.3	3.9

management, montmorillonitic soils are more productive than kaolinitic soils. The difference can be attributed mainly to a more gradual release of soil nitrogen in the montmorillonitic soils, with appreciable mineralization especially in the late vegetative and early reproductive stages of the rice plant (Yanagisawa and Takahashi, 1964).

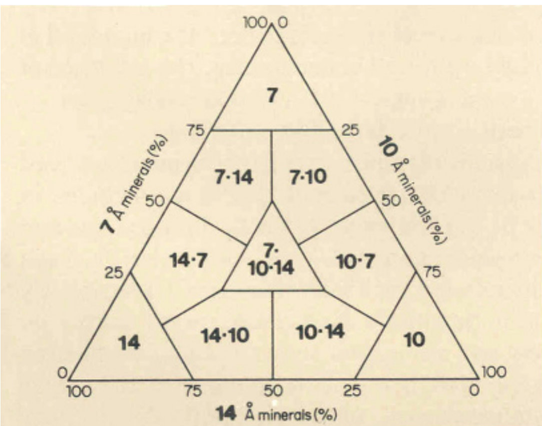
An extensive study of the clay mineralogy of the surface horizons of paddy soils in tropical Asia is reported by Kawaguchi and Kyuma (1974b).

Their study made a semiquantitative determination of the important clay mineral species:

- 7Å minerals, mainly belonging to the kaolin group,
- 10Å minerals, mainly micaceous clays (*illites*), and
- 14Å minerals, mainly smectite or montmorillonitic clays, with varying amounts of vermiculite and aluminum-interlayered vermiculite-chlorite intergrades.

According to the relative importance of component groups, 10 classes of clay mineral composition were distinguished, as indicated in Figure 2 and Table 4.

From these and other analytical data pertaining to the surface soils of paddy fields in Asia, Kawaguchi and Kyuma (1977) developed the notion of *inherent potentiality,* determined by mutually interrelated characters pertaining to base status, texture, and clay mineralogy. Together with two other groups of



2. Triangular diagram for grouping clay mineral compositions. (Kawaguchi and Kyuma, 1977)

Table 4. Distribution of surface soils over different clay mineralogy groups.[a]

Country	Distribution (% frequency) of surface soils over given clay mineral group									
	7	7–10	7–14	10	10–7	10–14	14	14–7	14–10	7–10–14
Bangladesh	0	13	13	0	7	0	0	10	26	30
Burma	0	16	13	0	2	2	0	25	6	36
Cambodia	31	0	34	0	0	0	0	28	0	6
India	3	6	14	0	10	4	9	23	9	23
Indonesia	20	0	18	0	0	0	28	31	0	0
Malaysia	34	2	24	0	0	0	0	39	0	0
Philippines	4	0	9	0	0	0	37	4	0	0
Sri Lanka	39	17	18	0	0	0	6	17	0	3
Thailand	19	21	46	0	1	0	3	7	0	4
Tropical Asia	15	9	22	0	3	1	11	23	5	11

[a] Adapted from Kawaguchi and Kyuma, 1977

characters related to organic-matter status and phosphorus status, inherent potentiality is used for fertility evaluation of soils. In terms of mineralogy, the inherent potentiality of soils of similar texture decreases with an increased dominance of kaolinite (7Å clay minerals) over the other clay minerals (10Å and 14Å groups).

In pluvial rice lands where the soil mineralogy reflects both the local parent material and the degree of weathering. the relation of mineralogy to the performance of rice with comparable management and similar rainfall is usually clear. Soils from basic rocks are better than soils from acidic rocks. If soils with parent materials derived from similar rocks are compared, the degree of weathering and hence the related mineralogical composition becomes an important productivity-determining factor.

The strongly weathered soils on old basalts of the Pleiku area in Vietnam, which do not contain any appreciable amounts of weatherable minerals and in which the clay fraction is dominated by iron oxides and kaolinite (oxidic families), are poor soils for rice. They are, however, extensively used under shifting cultivation where rice is grown only one year and the land is abandoned in the second year. Even with a better level of management, yields remain low. The situation is markedly different on soils derived from younger basalts in the same general area of Vietnam. Even though rice is also grown in shifting cultivation pattern, yields are higher, and rice is grown for 2 or 3 years before the land reverts to fallow. With inputs, e.g. fertilizer, such soils can be continuously cropped, and pluvial rice does well year after year.

Another example of the relationship between soil mineralogy and the performance of dryland rice is in the Philippines. On relatively young sediments of pyroclastic origin (water-transported volcanic ash) in southwestern Luzon (Batangas and Cavite provinces) and in other young volcanic areas of the Philippines, continuous cropping — including a yearly crop of dryland rice — is normal. These soils contain considerable amounts of weatherable minerals in the coarse fractions, and 2:1 lattice clay (mainly smectite) and varying amounts of allophane in the clay fraction. With high-level management, dryland rice yields as high as 7 t/ha were reported (De Datta and Beachell, 1972).

Older volcanic formations on Luzon, including both pyroclastic sediments and lavas, are much less productive as dryland rice land. Such older soils are mainly Udults, with less weatherable minerals in the silt and sand fractions, a predominantly kaolinitic clay fraction, and much lower base saturation of the profiles. Pluvial rice is grown in a shifting cultivation pattern for 1 or 2 years after clearing land of forest, shrub, or savanna vegetation, after which the land is abandoned. These two contrasting groups of Luzon soils have a similar topography; they are both fine clayey and have similar rainfall patterns, thus illustrating the importance of mineralogy on the performance of the rice crop.

In lowland rice areas, where parent materials were mainly transported, similar although less clear-cut relationships between productivity and the soil mineralogy are found. On a regional scale, differences in productivity of aquatic rice lands can be related to mineralogy of the catchment areas from which the transported soil material came.

As in pluvial rice lands, the age of the soil-forming materials and, hence, the degree of weathering as reflected in the mineralogy of both the clay and coarser fractions, are important in aquatic rice lands. Levels of production at low management level under comparable hydrological conditions vary distinctly with the age of the lowland landforms. As a general rule, rice land on recent alluvial deposits produces higher yields than that on alluvial terraces, and within terraces a clear distinction can be made according to age. The scattered available data point to differences in mineralogy, especially clay mineralogy, as the cause; soils become more kaolinitic with age.

An example of regional differentiation in productivity of lowland rice, which is primarily related to age of the landforms and hence to mineralogy, can be seen in Malaysia. The landforms are, on the whole, older on the coastal plains on the northeast coast (Kelantan) than those on the Keddah and Perlis coastal plains on the west coast. While the mineralogy of the coarser fraction does not differ much there is a clear difference in clay mineralogy (Table 5).

The dominance of kaolinitic soils on the Kelantan plains and the accompanying low nutrient status result in the relative low productivity of paddy

Table 5. Frequency (% occurrence) of soils with different kaolinite contents in the Surface layer in three regions of Malaysia (Kawaguchi and Kyuma, 1969b).

Soil	Frequency (%) of soils with different kaolinitic contents			
	<35	40–50	60-75	>80
West-coast riverine	6	44	31	19
West-coast marine	62	31	7	
East coast	0	0	25	75

lands on those plains (Soo Swee Weng, 1975). Paddy yields from the less kaolinitic coastal plain soils of Keddah and Perlis are higher with similar water regimes and management levels. Paddy yields are from 2 to 3.5 t/ha in Keddah and from 1 to 2.5 t/ha in Kelantan.

Table 5 shows that marine sediments are less kaolinitic than riverine sediments in West Malaysia. This is a rather general phenomenon in rice-growing deltas of tropical Asia and is explained by the neoformation of 2:1 layered clays, mainly montmorillonite, when the sediments are influenced by seawater.

Thus, even where the river deposits inland may be moderately to strongly kaolinitic because of predominance of strongly leached soils and the presence of kaolinitic formations in the catchment areas, the marine zones of such rivers are less kaolinitic and have a higher inherent production capacity for rice. But in coastal marine areas with acid sulfate soils the negative influence of high soil acidity supersedes the influence of a favorable clay mineralogy.

Neoformation of montmorillonitic clay also occurs in hydromorphic areas of inland valleys where the adjacent formations are high in bases. The bases and silica required for neoformation enter the valley soils by surface flow and interflow. In highly weathered landscapes also, paddy soils in such valleys are often less kaolinitic than the surrounding soils. An increased montmorillonite content may cause the formation of Vertisols in the lower aspects of drier landscapes where the surrounding areas are less kaolinitic.

In general terms, the neoformation of montmorillonitic clays enhances the quality of rice lands occupying such valleys, although secondary effects, such as zinc deficiency and increased salinity and alkalinity (especially in the more arid areas) may lower productivity.

The mineralogy of rice soils can also be improved by the deposit of mineralogically richer sediments. In lowlands such sediments are brought in by floodwater from rivers and by irrigation. The improving action of the floodwater sediments depends, of course, on the source of the floodwater (Hauser and Sadikin, 1956).

In areas that had active volcanoes during recent geological times, volcanic ash deposits cause enrichment of weatherable minerals in the surface soil. The rice lands in such areas (e.g. parts of Java and of Luzon) are among the world's most productive.

Even though regional comparisons indicate the importance of the influence of the soil mineralogical composition on the productivity of rice lands, quantitative data on the relationship are scattered and incomplete. At best, we can point out that the kaolinitic soils, with few or no weatherable minerals in the sand and silt fractions, always have low productivity. Soils with a high content of weatherable minerals and of 2:1 lattice type of clays, especially montmorillonite (smectite), have a higher potential. But how much and what kind of the better clays should be present to achieve optimal conditions for rice growing is not known. Further research is needed on the subject.

ORGANIC MATTER AND ORGANIC SOILS

Relationships between a soil's organic matter content and its productivity for rice are not clear; no systematic studies in this respect have been reported. The relationship is best examined by considering the most important function of soil organic matter, specifically humus in terms of growth of the rice plant and the behavior of soils in rice fields. The role of organic matter is mainly positive, but organic matter at high levels asserts a negative influence on rice growth.

Humus, the more or less stable portion of organic matter in soils, generally increases the water-holding capacity of mineral soils. Where even a slight decrease in the water-holding capacity of soils would reduce crop yield, the role of humus becomes proportionally more important. This can be observed in pluvial rice land with soils of sandy or coarse loamy texture where the clay mineralogy is dominantly kaolinitic and where rainfall is marginal. In dry periods, rice on spots of soil with a slightly higher organic content or with a somewhat deeper humic A1 horizon will stand out as less stressed by drought.

Where the mineral portion of soils is more clayey and where the clay mineralogy is more favorable, or both, the relative influence of humus on water-holding characteristics diminishes. The importance of the role of the organic fraction of the soil diminishes if crop water is assured as in bunded, leveled paddy lands. With perfect water control, the water-holding properties of the organic fraction do not reflect in the performance of the rice crop.

Organic matter has a positive effect on soil aggregation. A stable soil structure has many practical aspects related to crop production. The humus fraction plays the major role in this respect bur fresh organic matter in the process of decomposition is also involved in maintaining soil structure.

The role of organic matter in maintaining a stable soil structure is of primary importance for nonbunded, nonleveled pluvial and phreatic rice lands, but is unimportant in puddled rice lands, where the soil structure in the usual sense of the word is destroyed.

The role of organic matter in maintaining or improving soil structure assumes importance where various upland crops are grown in rotation with rice. Restoration of a good tilth after a wet rice crop is poor in soils with a low organic carbon content (e.g. less than 0.6%) as compared with that in more humic soils of similar texture and clay mineralogy.

An important characteristic of soil humus is its capacity to retain cations and, hence, its influence on the nutrient status of soils. The cation exchange capacity (CEC) varies from 1 to 3 meq/g of organic carbon. In soils with a low CEC by clay minerals, the retention of cations depends mainly on humus. In rice lands this aspect of the role of humus is of great importance in soils when a sandy texture combines with a kaolinitic clay mineralogy.

Organic matter may supply large amounts of phosphorus and, particularly, nitrogen to the rice plant. Even with good fertilizer practice, wetland rice depends on mineralization of organic soil nitrogen for more than 50% — often for more than 75%—of its total nitrogen requirement (Broadbent, 1978). The steady supply of nitrogen by organic matter in flooded soils is considered particularly important in obtaining high yields (>6/ha) in Japan (Tanaka, 1978).

Organic soils

The occurrence of highly organic soils is common in lowlands of zones without a dry season, or with only a short dry season. Soils high in organic matter have various names. The terms peat soils and muck soils are most commonly used for rice-growing soils, but Histosols is the modern term for organic soils in both *Soil taxonomy* and in the *FAO-Unesco soil map of the world.*

Histosols are defined as soils with more than 20% to 30% organic matter (12–18% organic carbon) in 40 cm or more of the upper 80 cm of the profile. Not all highly organic soils are Histosols. In Japan, Matsuzaka (1969) defines peat soils as soils with at least 20 cm of peat in the upper 50 cm of the profile, with peat being soil material with 20% or more humus. Paddy soils in Japan in the category of muck soils should have a muck layer of 20 cm or more in the upper 50 cm, with muck defined as soil material with 10 to 20% humus. Both categories are waterlogged and have a low topographical position. Most of the muck soils and some of the peat soils of Japan are not Histosols. Soepraptohardjo and Driessen (1976) indicate that Histosols cover about 27 million hectares in Indonesia, 60% of which have more than 65% organic matter to a depth of 50 cm or more (Polak, 1952).

Soils high in organic matter, therefore? range from mineral soils with about 10% organic matter in the surface layers to pure peat soils with little or no mineral fraction to a depth of many meters. The small proportion of peat soils used for rice are mainly found

- where the surface layer is composed of mineral soil to a depth of about 20 cm, as is often the case on the fringes of peat areas where covers of recent river alluvium occur;
- where the organic layers are shallow, and where a mineral subsoil is found at a depth of less than 50 cm; or
- where the soil material does not contain much more than 20 to 25% organic matter after reclamation and drainage.

Most of the extensive deep-peat areas in tropical Asia are not cultivated; those that have been reclaimed are only rarely used for rice growing (Soepraptohardjo and Driessen, 1976; Kanapathy, 1975). The general trend is for oligotrophic (nutrient-poor) peat soils more than 1 m deep to remain uncultivated. Most experimental yields of rice on such soils are low and returns on investment for clearing, burning, drainage, and fertilization are discouraging.

The potential of highly organic soils for rice growing varies considerably; most of such soils present only limited possibilities. An important limitation is their low bearing capacity. At a high level of organic matter and with continuously high groundwater no traffic pan is formed. The result is that land preparation cannot be mechanized and even the use of animal traction is generally impossible (see Chap. 4, Fig. 3). In addition, wet soils that are high in organic matter in the superficial layers offer a poor foothold for the rice plant and make the crop extremely vulnerable to lodging.

The nutrient status of the highly organic paddy soils varies with the nature of the organic matter and the mineral portion. Only a small proportion of such soils is eutrophic (nutrient-rich). Nitrogen, although present in the organic matter, becomes available only if liberated by mineralization after drainage; then often it is liberated in excess quantities. In organic soils, phosphorus, potassium, zinc, copper, and molybdenum are also commonly deficient. Perhaps partly due to such deficiencies the incidence of blast (*Pyricularia oryzae*) and brown spot (*Helminthosporium*) is often high on such soils (Ikehashi and Ponnamperuma, 1978). In acid paddy soils that are high in organic matter growth-inhibiting organic acids affect rice roots and lead to low productivity or crop failure (Takijima, 1963). A negative effect of groundwater in peat soils can be seen in dominantly mineral-soil paddies adjacent to peat soils areas; drainage water from the peat areas seriously inhibits growth of rice.

The transformation of raw peat lands into agricultural land involves a complex process. First, drainage is required to make crop growth possible, even in the case of rice. Drainage diminishes or eliminates toxicity of organic substances and increases the availability of various nutrients. Second, in predominantly organic soils, surface burning of the peat is often required to create a mineralized plow layer with physical and chemical characteristics favorable for plant growth. But even when such improvement measures are taken, most reclaimed peat lands remain unfavorable for rice growing and are used mainly for other crops.

Another reclamation problem, serious particularly for deep peat soils, is that of subsidence after drainage as a result of decreased water content, compaction, and mineralization. Thus, after a number of years the surface of drained organic soils becomes close to the groundwater level, and the disadvantages of poor drainage will again predominate. This effect can be offset by regulation of the depth of drainage to the minimum required by plant growth, but in most cases such measures are costly and technically difficult to achieve. Rice, which will remain a poor crop on such a soil, could not be expected to pay for the reclamation costs and the high recurrent costs of maintaining a reasonable environment for its growth.

CALCAREOUS SOILS

Soil taxonomy recognizes the presence of carbonates in the fine earth fraction as a characteristic for defining the soil family. Calcareous soils are those where the fine earth fraction in the profile section between 25 and 50 cm effervesces with cold dilute hydrochloric acid. In many cases the surface soils will also be calcareous, but it may be free of calcium carbonate according to the *Soil taxonomy* definition, and may even have a slightly acid reaction. In view of the shallow rooting of rice and of the dominant importance of the puddled layer in the aquatic rice land, we consider calcareous rice-growing soils as those with a calcareous surface layer.

The presence of free calcium carbonate in the surface horizon of rice-growing soils may be either related to the parent material or due to secondary lime accumulation. Primary lime is found in soils derived from materials such as soft limestones and marls. Secondary lime precipitates from groundwater high in calcium bicarbonate by evaporation or escape of gaseous carbon dioxide, and under aquatic conditions, through accumulation by mollusks.

Few pluvial rice lands have calcareous soils. A prerequisite for accumulation or maintenance of free calcium carbonate in the surface of freely drained soils is a dry climate with an excess of evapotranspiration over rainfall. Dryland rice cannot be grown under such climatic conditions. Some pluvial rice lands are found on Rendolls in wetter climates, but even those surface soils are calcareous only where erosion has exposed the calcareous subsoil. Rice growth is always poor on such spots.

Calcareous rice-growing soils are, therefore, found mainly in lowland water-deposited sediments. Soils on sediments with a high primary lime content are widespread in arid and semiarid areas, especially where the catchment areas contain limestone and basic igneous rocks, or soils derived from them. Such conditions predominate in large parts of India, where soils of paddy lands with a high pH are usually calcareous throughout.

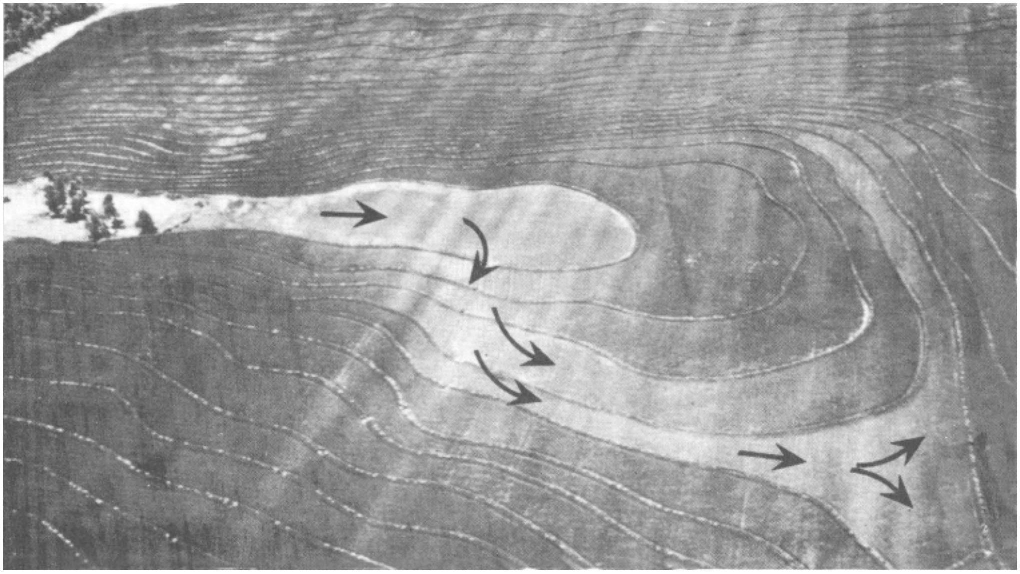
Rivers that run some distance through areas with basic parent materials may deposit calcareous sediments in the higher rainfall areas. That is the case for the Ganges alluvium, which is calcareous throughout the river's course, even in the lower Ganges basin in Bangladesh where rainfall is from 1,250 to 2,250 mm (Brammer, 1971b).

Calcareous soils in marine sediments are not particularly widespread because fresh marine sediments usually contain pyrite (FeS_2), which oxidizes to provide sulfuric acid and dissolves calcium carbonate. Nevertheless, some calcareous soils occur in rice fields of coastal areas.

Secondary lime accumulation in lowland rice-growing soils may occur irrespective of climate and parent materials. Biological calcium accumulation, mainly as mollusk shells, with even small amounts of calcium in flood or irrigation water, can be found in both marine and alluvial wetlands irrespective of the rainfall regime. In parts of Central Luzon, Philippines, the surface soils of irrigated rice lands contain considerable amounts of mollusk shells, mainly fragmented to sand and silt-sized particles. The original parent material was not calcareous and the subsoil of the areas has no free calcium carbonate and a slightly acid reaction.

Of course such calcium carbonate accumulation is possible only if the rate of accumulation of calcium carbonate exceeds the decalcifying effects of flooding and soil reduction alternated with drainage and oxidation.

Precipitation of calcium-magnesium carbonates from irrigation water was described in rice land in Arkansas, USA (Ferguson et al., 1977). The accumu-



3. Flow pattern of irrigation water high in calcium bicarbonate and the resulting carbonate accumulation in the soil are reflected by chlorosis of rice plants in this Arkansas, USA, rice field. The chlorosis is probably caused by zinc deficiency. (Photo courtesy of J.A. Ferguson)

lation was strongest (equivalent to more than 25 t Ca/ha) in the highest field, which first received the irrigation water, and decreased in successive lower fields that were supplied by overflow water. The pattern of the water flow (Fig. 3) and the resulting carbonate accumulation was reflected by chlorosis in the rice plants, presumably due to zinc deficiency.

Indeed, a main disadvantage of calcareous soils for wetland rice is that zinc deficiency and, sometimes, iron deficiency are induced (Tanaka and Yoshida, 1975). For instance, *Khaira* disease, which is widespread in India on calcareous soils (whether or not highly alkaline), is due to zinc deficiency. Not all rice grown on calcareous soils shows zinc deficiency, but the deficiency will almost certainly develop if such soils are sufficiently high in organic matter to cause appreciable soil reduction upon flooding.

Iron deficiency on calcareous soils is also fairly widespread. It is found mainly where rice is grown on calcareous soils with no flooding, or with intermittent flooding, although in California, U.S., iron deficiency develops on flooded rice lands. In this respect, observations by IRRI researchers in Pangasinan province, Philippines, are of interest. There. calcareous soils with biological lime accumulation cause iron deficiency symptoms in the young, nonflooded, rainfed rice crop. Upon flooding, the iron deficiency symptoms disappear; but when flooding and subsequent reduction of the plow layer is maintained for a long period, zinc deficiency appears in spots. By a regime of alternate flooding and drying of the paddy both deficiencies are avoided to a large extent in the area, but such a water regime is not conducive to highest yields.

The tendency of calcareous rice soils to fix zinc, together with unavailability of iron in such soils when they are not sufficiently reduced, diminishes the soils' quality for rice growing. Application of sulfuric acid may dissolve the excess of calcium carbonate and lower the pH; such corrective measures are costly and have been applied locally in Japan, and on a large scale only in the United States.

SALINITY AND ALKALINITY IN RICE LANDS

Salinity occurring in rice-growing areas is caused mainly by sodium chloride, but sodium sulfate is also found locally in harmful concentrations. High concentrations of the soluble salts of calcium and magnesium are not important in relation to rice because they occur mainly in the most arid zones where rice is rarely grown.

Effect of salinity and alkalinity on the rice plant

Rice is generally reported as a moderately salt-tolerant crop, but no rice variety can withstand high salinity throughout its growth cycle, and no rice is grown as a dryland. crop in salt-affected land. Soil solutions high in sodium chloride with electrical conductivity values of 6–10 mmho/cm are associated with 50% decrease in yield, but sodium sulfate is considered somewhat less toxic. Such values have only minor significance in the field.

First, the salt tolerance of rice varies throughout its growing cycle (Pearson and Ayres, 1960). The plant is tolerant during germination but young seedlings are sensitive until the age of at least 1 weeks. Damage to the rice plant during transplanting increases its sensitivity to salinity. An increase in salt tolerance occurs during tillering, but the plant again becomes sensitive during flowering. Sensitivity again diminishes during the maturation period.

Second, varieties differ considerably in susceptibility to salinity (Castro and Sabado, 1977). Farmers growing rice in salt-affected soils have, without intent, naturally selected varieties with salt tolerance.

Finally, at a given salinity level rice plants are more salt sensitive at high light intensity and lower relative humidity, and can withstand a certain level of salinity better during the wet than during the dry season.

High alkalinity caused by sodium bicarbonate and sodium carbonate affects rice. Various factors are involved in depressing yields. The high pH of alkaline soils induces zinc deficiency. A high bicarbonate level may cause calcium deficiency by lowering the level of dissolved calcium, which is precipitated as calcium carbonate. Potassium deficiency and excess of reducing substances may be other growth-inhibiting factors (IRRI, 1972). Iron deficiency in intermittently flooded alkaline rice lands has been reported.

Strongly alkaline soils are invariably high in adsorbed sodium. Although rice tolerates such high levels better than most of other crops, it appears that a sharp decrease in yield is caused by an exchangeable sodium percentage of 50 or more. Most of the time, however, it is difficult to isolate the effect of the high sodium adsorption from that of high pH.

A management problem for rice on highly alkaline soils is that applied ammonium or urea nitrogen is easily lost by ammonia volatilization.

Causes of salinity and alkalinity in rice soils

In general soil salinity is caused by the presence or by intrusion of seawater, or by surface evaporation of soil water of an initially low salt content. Whereas intrusion of seawater may cause harmful salinity even in high-rainfall areas, evaporative concentration of salts is important only where evaporation exceeds precipitation. Both mechanisms can act simultaneously so that high salinity is often caused by intrusion of moderately saline water, the evaporation of which concentrates the salts.

Harmful high alkalinity is related principally to the presence of sodium carbonate and sodium bicarbonate. Accumulation of those salts in the soil and soil water occurs when groundwater with a high content of bicarbonate ions evaporates. Initially, calcium and magnesium carbonates precipitate upon evaporation, immobilizing part of the bicarbonate ions. But if excess bicarbonate is present (so-called residual alkalinity), high pH values will develop, even at initially low concentrations of sodium bicarbonate. In strongly alkaline soils, sodium carbonate and bicarbonate become prevalent salts, and sodium will replace calcium and magnesium in the clay complex (sodic soils). This leads to the formation of sodium clays, which are strongly dispersed and, hence, highly impermeable to water.

Highly alkaline conditions due to residual alkalinity in the rice-growing zone are limited to semiarid and arid areas. Chances for residual alkalinity in groundwater and surface water are especially high where granitic rocks dominate in the catchment areas.

In marshy areas alkalinization may result from microbial reduction of sulfate. In the process, organic matter is oxidized to bicarbonate while sulfate is transformed to gaseous hydrogen sulfide (Janitzky and Whittig, 1964).

Types of saline and alkaline land

Depending on their source and occurence in the landscape, forms of soil salinity and alkalinity may be classified as:

- marine salinity, derived directly from seawater intrusion either by surface flow or by seepage;
- interflow salinity or alkalinity derived from lateral influx of drainage water mineralized by weathering of salt-bearing crystalline or sedimentary rocks situated above the level of the rice-growing lands;
- groundwater salinity or alkalinity, typically in depressions where ground-

water occurs at shallow depth and salts have accumulated near the soil surface because of capillary rise from the water table; and

- surface water salinity or alkalinity due to evaporation of soil moisture brought in by river floods or irrigation and which, because of low permeability of the soil or rapid evaporation, has no chance to drain vertically.

There are, of course, transitions between these forms of salinity.

MARINE SALINITY. Marine salinity is confined to low areas bordering sea coasts. Some saline land is found along every coast, but the width of the affected area varies greatly. Marine salinity is limited to land that is below the high-tide level and that is not protected by man. There are important differences in degree of salinization, depending on climate, tidal regime, and regime of streams entering the coastal plains. Generally speaking, salt accumulation and severeness of salinity increase in the drier climates and diminish strongly in an equatorial climate without a pronounced dry season. Extremely saline deltas are found in arid climates. There, the intruding seawater evaporates, leaving behind salt crusts and groundwater with a salt concentration higher than that of seawater. On the other extreme, salinity in the rainy perhumid zones, e.g. East Sumatra and the coastal area of Kalimantan, Indonesia, is confined mainly to the twice daily inundation of tidal flats that are normally occupied by mangroves. Little rice is grown on land influenced by either of the two extreme conditions of marine salinity.

In the arid zones, good quality water to reclaim the land for rice is often not available; the lower Nile delta is an exception. In the perhumid zones, the tidal land offers a score of difficulties for reclamation, such as poor accessibility and poor soil conditions (potential acid sulfate soils) (Moormann and Pons, 1974).

Most rice land influenced by marine salinity is found in zones with a monsoon type of rainfall. Such land is widespread in the lower part of the major and minor deltas of Asia, where due to increasing population pressure, rice cultivation extends to areas well below the levels of high tides. In such areas it is not possible to completely control salinity by the traditional method of ponding fresh water. In a few areas such land has been desalinized by empoldering and artificial drainage as in the Red River delta in northern Vietnam.

Many coastal rice-growing zones in tropical Asia, however, are not or at least not completely, protected against periodic saltwater intrusion. In this respect, the coastal areas periodically subjected to floods caused by cyclones or typhoons suffer most unless they are protected by high dikes. Such floods affect much rice-growing land around the gulf of Bengal in India and Bangladesh in the wet season. Crop damage may vary from slight (if the flood strikes when the plants are in a salt-tolerant growth stage, i.e. seedlings, ripening) to severe (if the flood coincides with flowering). Protection against this type of unpredictable, generally catastrophic salinity cannot be achieved by improved water management at the farmer's level, or by the growing of salt-tolerant varieties. Major engineering measures such as dike building and empoldering are required for sustained improvement. Rice growing in such areas is hazardous, and the benefits of improved local water management and improved salt-tolerant varieties can be undone by one tidal wave.

The tidal regime influences the degree of marine salinity. Seawater penetrates deeper inland where the tidal amplitude is large. A large tidal amplitude can, however, be helpful in reclamation. The land, protected by dikes, is drained during low tide, and no salt water enters the protected area during high tide. Reclamation in such coastal areas is often pushed much further seaward than it is along coasts with small tidal amplitudes. Often the mean tide level as well as the spring tide levels fluctuate seasonally. In most of the coastal areas in Thailand and in the Mekong delta spring tides are highest in the dry season, leading to strong seasonal salinization. When sufficient fresh water is available during the wet season the salts are washed away and a good rice crop can be grown. In contrast, high tide levels in the Philippines coincide with the onset of the wet southeast monsoon (May-July) and farmers are often obliged to delay planting for several months. If irrigation water is available during the dry season, however, rice can be grown on the same fields without any risk of salinization.

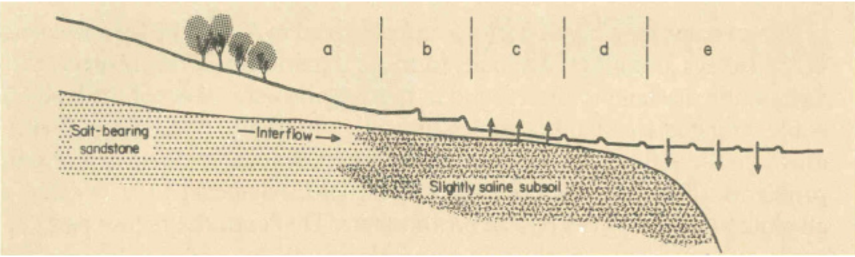
The influence of rivers and streams entering coastal areas varies from place to place, which means the relation between salinity and river regime must be studied locally. Man's interference with river flows in areas with potential marine salinity has had both positive and negative effects. While the tapping of fresh river water is a helpful factor in reclamation of saline coastal lands, a decrease in discharge of coastal rivers due to water use may lead to salinization of other areas.

SALINITY AND HIGH ALKALINITY BY INTERFLOW. Salinity by interflow can be expected in areas with salt-bearing crystalline or sedimentary rocks at relatively shallow depths in the higher parts of the landscape. Seasonally high rainfall promotes the transfer of salts from the weathering zones to spring levels in valleys and along foot slopes. Drainage water from weathering zones of felsic rocks such as granites often has alkalizing properties and may result in highly alkaline soils near spring levels of interflow water. Interflow salinity is quite common in monsoonal areas with a pronounced dry season.

Rice-growing areas influenced by this type of salinity or alkalinity are found in the Deccan plateau of India, and in the northeast region of Thailand (Sinanuwong and Takaya, 1974a, b). Smaller areas are found in most dry zones of countries where lowland rice is grown.

The relationship between salinity and climate is clear on the rice-growing plains along the Vietnamese coast from Phan Rang to Hue. Interflow salinity and alkalinity are common on the dry plains of Phan Rang and Phan Thiet, but diminish sharply toward the higher rainfall zones to the north. They disappear entirely on the high rainfall plains, such as those of Danang and Hue.

Where salt-bearing rocks are rare or absent, salinity by interflow is generally



4. A cross section of a slope of a lower valley shows the process of sallnlzatlon as In northeastern Thailand. Arrows indicate net water movement during part ofthe year; *a* is nonsaline dryland; b is nonsaline pluvial-anthraquic rice land; *c* is waste land, strongly saline due to evapotranspiration of slightly saline groundwater at shallow depth; d is phreatic-anthraquic rice land, periodically affected by salt; and *e* is phreatic-anthraquic or fiuxial rice land that is nonsaline.

unimportant. For instance, a sharp distinction exists between the broad northeast Thailand peneplain and the geomorphologically and climatologically similar peneplain in Cambodia, north of the Ton Le Sap lake. In the former, salt-bearing sandstones of the Mesozoic age (Khorat group) are an important source of salinity in rice lands, but such saiinity in the Cambodian peneplain has not been reported.

In areas with interflow salinity, the lower parts of toposequences tend to be saline at the surface or at shallow depth. Salt moves down from salt-bearing rocks by interflow and appears at the surface in the lower parts of the landscape where salt accumulates in the upper horizons because of evapotranspiration. Suppression of salinity by ponding good quality rain and irrigation water in the bottomlands of valleys leads to a distribution of salt-affected lands in rice-growing areas as schematically represented in Figure 4. An actual example from northeastern Thailand is seen in Figure 5.

5. Interflow salinity affects rice lands in northeastern Thailand. Seen here are four zones (*a* to *d*) that correspond to the same zones in Figure 4.

Many examples of these patterns are observed in Asia. The land-use pattern in the valleys around Hyderabad, India, is remarkable in this respect. Pluvial anthraquic rice land is often found in the intermediate aspect of the landscape, while irrigated rice land occupies the valley bottoms. Two crops of rice are grown in the valley bottoms with water from tanks, and with no severe salinity problems. The zone between the pluvial and irrigated paddy is saline and alkaline to a varying degree. In northeastern Thailand, the higher parts of the landscape are mainly in shifting cultivation while in a score of places, people gather salt from the saline zone above the paddy fields. The transition between salt-affected zones in lower slopes and nonsaline paddy fields below is remarkably sharp. Often, the outside of the paddy bund bordering a saline zone may show salt efflorescence at the surface, while the inside of the bund is not or is only slightly saline.

Saline-alkali spots tend to be confined to the areas near the spring levels; saline but nonalkaline soils also occur toward the lower areas, as e.g. in the dry zone of Sri Lanka.

Aggravation of interflow salinity and, indirectly, of groundwater salinity in the depressions is influenced by the land-use pattern on the nonsaline dryland soils bordering the valleys and depressions where such salinity occurs. Where these drylands are under a natural bush or forest vegetation, or under a balanced shifting cultivation pattern in which woody species can regenerate, interflow is limited because tree roots intercepr much of the water percolating in the rainy season. When the catchment areas are completely cleared, interflow increases and the water table in depressions may increase concurrently. This can lead to a local worsening of lower-slope salinity.

GROUNDWATER SALINITY AND ALKALINITY. Groundwater salinity and alkalinity are associated with groundwater at shallow depths. An excess of evapotranspiration over rainfall causes a net upward movement of water through the soil by capillary action and leads to surface efflorescence of salts during dry periods. This mechanism plays an important role in areas affected by seawater and in areas with interflow salinity, but it is most typical in inland areas with large depressions occupied by alluvial and lacustrine plains and by river terraces of different ages.

The high water table may be due to continued influx of surface or groundwater from elsewhere. Irrigation schemes without proper drainage often lead to this type of salinization. For instance, in the southern Indus valley in Pakistan (Sind province), large areas became strongly saline after the introduction of extensive irrigation, which led to a rise of the water table from a depth of 20 to 30 m to 1 to 2 m within 20 years. The groundwater itself need not be saline, although it often is, because long-term evaporation of continuously recharged water of a low salt content inevitably leads to strong salinity in arid climates. Often, the most saline soils are concentrated in the lower parts of the landscape, e.g. around intermittent lakes in backswamps and in abandoned river channels.

Land affected by groundwater salinity is often most profitably used for rice growing, and paddy cultivation on salt-affected land is rapidly increasing in many parts of Pakistan and India.

SURFACE WATER SALINITY AND ALKALINITY. Alluvial depressions in areas with semiarid and dry monsoonal climates collect and retain part of the surface runoff from higher areas. If the permeability of the soils in the depression is slow and little percolation takes place, surface salinization occurs by evaporation of soil moisture and surface water even though such areas have a dry, nonsaline subsoil.

As in the case of groundwater salinity, microtopography plays an important role in salinization, with the lowest spots most strongly affected. Most of the highly alkaline soils near Lahore, Pakistan, where rice is grown on a large scale, are in this category. The high levels of exchangeable sodium in such soils cause strong dispersion of the clay and thus low permeability, which prevents internal drainage and increases the chance for further accumulation of soluble salts.

Variability and dynamics of salinity and alkalinity in rice fields

Due to the high mobility of water-soluble salts, salinity is extremely variable in time and place. Salt on or near the surface may be removed by vertical and lateral drainage at the onset of the wet season or salinity may be diluted by fresh water. In low areas salt may be brought in by seepage or surface runoff, and salt may concentrate on slightly higher, nonflooded spots by evaporative concentration.

As noted, coastal salinity often depends on largely unpredictable factors such as cyclones (e.g. around the Gulf of Bengal) or, less frequently, on the flow cycle of rivers that provide fresh water during the rice-growing season (e.g. in the Casamance and Gambia river estuaries in West Africa). Sudden seawater infringement may destroy a rice crop completely or may do relatively little damage, depending on the stage of crop development. When rice is planted at different dates in a salt-affected area, a single short-duration seawater infringement may produce a checkerboard effect of badly and slightly affected fields.

In all paddy fields affected by salinity, the amount of rainfall and its distribution will alter the salt injury pattern from year to year, or even within a season. The major production constraint in such lands is crop insecurity. In a year with copious, well-distributed rain, injury may be minimal but in other years, crops may suffer when there is not enough rainwater or irrigation water to suppress salinity in the root zone during the critical stages of plant growth. The quality of irrigation water, especially when provided by smaller reservoirs, is also vari-

6. This rice crop in northeastern Thailand clearly shows the effect of microvariability of salinity.

able and salt contents tend to be higher in unusually dry years.

In most cases there is a clear microvariability of salinity and degree of injury of the rice crop (Fig. 6). Microrelief variations are one cause. In partially flooded fields, slightly higher spots are often distinctly more saline, because of evaporation from the soil and capillary rise of saline groundwater when the high spots are temporarily dry.

Typically, in northeast Thailand and similar salt-affected areas, old termite hills in paddy fields have a fringe of saline soils along their base where no rice will grow. Man-made irregularities such as somewhat higher strips along bunds may show a similar fringe salinity.

Microvariation in internal soil conditions such as miniscule differences in hydraulic conductivity of the soil profiles may also be involved in the typical spotty salinization. Furthermore, saltwater subsurface flow may follow preferential lines or aquifers, as in sandy lenses in a more clayey soil in sedimentary deposits. Microvariability and unpredictability of salinity make agronomic studies, including varietal testing for salt tolerance, extremely difficult.

Although alkalinity also is often spotty and shows lateral variability closely related to microtopography (Fig. 7), it is less variable in time than salinity. The movement of the readily soluble sodium bicarbonate and sodium carbonate is strongly hampered by the slow permeability of those dispersed clayey soils. Furthermore, the exchangeable sodium in alkaline soils is not readily mobile.

7. Rice land strongly affected by high alkalinity in Haryana state, northern India. Rice survives only in the lowest areas, seen here as darker because of soil moisture.

Reclamation and management of saline and highly alkaline soils for rice

The major reason that rice is grown on saline land, where virtually no other crop will grow, is the aquatic nature of the crop. Rice will grow on land that is highly saline when dry, provided the soil can be flooded with low-salinity water. Floodwater dissolves and dilutes the salt in the surface soil layers and drainage and percolation induced by ponding remove part of the salt from the rice plant's shallow root zone.

In most of the areas in Asia where saline land was reclaimed by ponding, no artificial drainage was provided and the salt was simply leached down to a level where it was no longer dangerous to the rice crop. Some salt may leave the affected area by natural drainage, through interflow, and by creeks and rivers, but a large portion remains in the subsoil.

In tidal areas, the natural surface drainage during the wet season can remove salt from the surface soil, but unlessdikes and flapgates are constructed, salinity returns in the dry season. For example, in areas adjacent to the sea on the Mekong delta of Vietnam, surface salt accumulates in the dry season. Water ponded in the paddies during the early rainy season is commonly drained to evacuate the salt and rice is transplanted only after later rains fill the paddies.

In several marine estuaries of West African rivers, saline mangrove land is similarly used (Moormann and Pons, 1974). The only land reclamation measure is the cutting ofthe mangrove. The crop is planted during the flood season after the fresh floodwater has diluted and washed out enough salt to allow rice to grow. When the seasonal floods subside, seawater reintrudes and the land reverts to a saline condition. Use of such unprotected saline land is frequently risky, especially if the river floods subside early.

Protection of such tidal land by dikes will decrease the risks of salinity damage, but there are disadvantages as well. Premature reclamation of mangrove marshes by diking in India and Bangladesh caused considerable land subsidence leading to increased seepage of saline water and greater damage from cyclonal floods (Nagaraja, 1964).

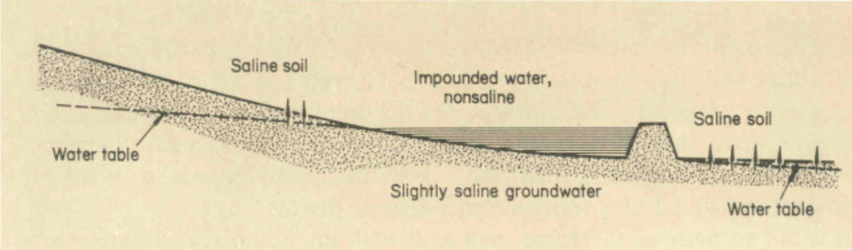
Rice cultivation is also advantageous for highly alkaline soils. Because of their poor permeability for water and the relatively low mobility of exchangeable sodium, the alkaline soils generally do not improve under paddy rice cultivation as quickly as saline soils. But in highly alkaline soils, flooding has a different beneficial effect. Chemical reduction of the surface soil after flooding increases the concentration of carbon dioxide, which leads to a drop in pH and an increase in dissolved calcium by dissolution of the calcium carbonate that is usually present in such soils. The decrease in pH (down to values between 7 and 7.5 if sacient organic matter is present) is favorable for the availability of phosphorus and many microelements, whereas the increase in dissolved calcium favors the removal of exchangeable sodium. The presence of rice plants seems to promote the mobilization of calcium and sodium beyond that in unplanted flooded soil (CSSRI, 1974).

Sodic soils are often amended with gypsum and pyrite in northern India and Pakistan, which help speed soil improvement. Nonamended paddies, however, will improve to the same level of productivity with more time.

Total elimination of sodicity is not always desirable for lands where rice is grown in rotation with winter wheat, such as in large tracts of northern India and Pakistan. That would drastically increase the permeability of those often silty and sandy soil and lead to greater losses of irrigation water when the land is used for rice. Although this excessive permeability could be diminished by puddling the paddies, such soil management would deteriorate the physical condition of the soil for the upland crop in the rotation.

In irrigation projects in saline areas, the tendency is to practice multiple cropping with wet-season rice followed by one or more intermediate or dry-season dryland crops. For economical use of irrigation water, this approach seems logical. But the dynamics of salinity are definitely against such an approach. When dryland crops are grown in the dry season with intermittent irrigation, a moist zone forms between the subsoil saline layers and the surface. Evapotranspiration becomes important and salinity develops rapidly in the surface soil layers.

The speed of salinization varies. Salinization has occurred within one dry season in medium-textured soils at Kalasin, northeast Thailand, and at



8. Land around small reservoirs often becomes saline because of' continuous evaporation of slightly saline water from an elevated water table.

Richard Toll in the Senegal River basin. At Kalasin, pluvial anthraquic rice land was irrigated during the dry season for a variety of dryland crops. At Richard Toll, irrigated paddy lands of a high quality on medium-textured Aridisols and fine-textured Vertisols were transformed to a sugarcane plantation. The Aridisols at Richard Toll became saline by capillary rise from a water-saturated subsoil within a few months. The salinization of the Vertisols in the surface-irrigated sugarcane plantation was slower but proceeded relentlessly, and the only economic solution appears to be a return to rice growing, using the available irrigation water for a smaller area. Many irrigation projects in the drier rice-growing areas suffer from the same lack of insight into the dynamics of salinity.

Salinization of nonsaline rice fields due to injudicious engineering is found in an increasing number of irrigation projects in areas with interflow and groundwater salinity. The storage of water in reservoirs and its transport through unlined irrigation canals above the level of the paddy fields in the low-lying areas generally lead to rising water tables. This frequently affects rice lands below and adjacent to canals and reservoirs but it can affect the salinity of large areas if no appropriate drainage is foreseen. When the upward movement of saline groundwater in such cases exceeds the downward movement of good quality rain or irrigation water, paddy lands will be affected by salt.

Such small salinized areas are typical in northeast Thailand adjacent to and below small reservoirs constructed since the 1950's in salt-affected lands (Fig. 8). This kind of localized salinity was also found below reservoirs on the Deccan plateau (Hyderabad area, India) and, to a lesser extent, in the dry zone of Sri Lanka. Generally speaking, in such reservoir construction, too little attention is given to the dynamics of salinity in the area, and the role of ponded water in paddy fields in establishing and maintaining nonsaline conditions is essentially not understood.

ACID SULFATE SOILS

On many coastal plains in the tropics, notably in Vietnam, Thailand, Indonesia, India, and several West African countries, large tracts of land are poorly productive or entirely unsuitable for agriculture because of acid sulfate soils. Except for their adverse acidity (pH 3.5–4.5) and its related toxic effects, acid sulfate soils have many characteristics favorable to wet-rice cultivation. The soils are naturally hydromorphic and the topographic and hydrologic setting is normally suitable for establishing paddies. Moreover, acid sulfate soils are generally well supplied with plants nutrients, partly because of relatively high contents of 2:1 clay minerals and organic matter.

It is not surprising, therefore, that soils with moderate acid sulfate conditions are often used for rice growing. Rice is grown on most of the 800,000 ha of acid sulfate soils in Thailand, and about half of the 1,000,000 acid sulfate ha in Vietnam. On the other hand, the seemingly favorable land type for rice in most acid sulfate soil areas often led to injudicious reclamation projects that ended in total failure as a result of strong acidification.

Our interest here is in occurrence and formation of acid sulfate soils, the adverse effects of acid sulfate conditions on the growth of rice, and the effect of flooding and reclamation measures on acid sulfate soil properties inasmuch as they relate to rice production. The emphasis is on acid sulfate soils in Thailand and southern Vietnam, with which the authors are most familiar. Soil salinity, which often occurs in acid sulfate soils, has been dealt with in the previous section; it is easily suppressed by ponding and leaching with fresh water, and in this respect differs from acidity, which is more difficult to amend.

Formation of acid sulfate soils

Acid sulfate soils are developed from reduced, nonacid sediments, high in pyrite and low in calcium carbonate — the so-called potential acid sulfate soils. In the tropics, potential acid sulfate soils are formed in the tidal mangrove marshes of coastal lowlands. In the often clayey sediments, which receive an ample supply of organic matter from the mangrove vegetation, sulfate from seawater is reduced to sulfide through the activity of sulfate-reducing bacteria and ultimately fixed as pyrite. If these near-neutral reduced pyritic sediments are ærated during natural or artificial drainage, pyrite is oxidized to ferric hydroxide and sulfuric acid. In the absence of sufficient acid-neutralizing calcium carbonate, the release of sulfuric acid lowers pH and leads to the formation of acid sulfate soils.

In mangrove marsh sediments, conditions for pyrite formation are most favorable in the profile layers that are subject to flushing of the soil material by tidal water. Less pyrite is accumulated in the continuously reduced substratum below the level of the lowest tide and in the upper strata of the sediments in the better drained parts of the marshes which are aerobic most of the time. The effect of tidal flushing is strongest in areas crisscrossed by tidal creeks, as are commonly found near the mouths of rivers and in areas surrounding lagoons. Such land is commonly characterized by sediments with dangerously high (2–6%) pyrite contents. In contrast, in the absence of tidal creeks the pyrite contents of the coastal muds tend to be much lower (0.2–1%).

Many factors complicate this simple picture. If coastal accretion is rapid, as along the present delta of the Irrawaddy River in Burma, the mangrove stage does not last long enough for appreciable pyrite accumulation. When there is a slowly rising sea level, thick deposits of pyritic sediments can be formed. Such conditions have led to the extensive areas with acid sulfate soils underlain by a thick deposit of potentially acid clay in the inland parts of the deltas of the Chao Phraya and Mekong rivers in Southeast Asia. Where riverine deposits have covered pyritic sediments to a depth of 50 cm or more, the acid or potentially acid substratum ceases to affect crop growth. In some areas, potentially acid sediments are overlain by peat, e.g. in parts of Kalimantan, Indonesia, and Vietnam.

There is natural acidification of pyritic sediments when the influence of the tides lessens, as with coastal accretion. In the somewhat higher terrains the pyritic soils may dry partially and aerate during dry periods. Aeration following artificial lowering of the groundwater, as in empoldering, has the same effect. The rate of aeration is generally so slow that buffering reactions involving alterations in the clay minerals keep pace with the release of sulfuric acid, and the pH does not normally drop below 3 or 4. However, if a potentially acid soil is sampled and the sample subjected to intensive artificial aeration during slow air-drying, acidification is extremely rapid and may give a pH between 1 and 3. Such low pH values are frequently cited as typical for potential acid sulfate soils, but they normally have little relevance to field conditions.

Oxidation of pyritic muds causes several distinct morphological changes. The normally dark-gray or greenish-gray color of the sediment changes to grayish brown and brown, and pale-yellow mottles due to ferric iron develop along pores and on faces of structural elements. Typical in acid sulfate soils are the conspicuous pale-yellow mottles of the basic ferric iron sulfate mineral jarosite, mineral that forms only at a pH below 4.

Taxonomy of acid sulfate soils in rice-growing areas

Potentially acid sulfate soils that have sulfidic materials within 50 cm of the surface are Sulfaquents. Acid sulfate soils that are seriously affected by soil acidification are Sulfaquepts. These soils have a sulfuric horizon characterized by a pH of less than 3.5 and jarosite mottles at less than 50-cm depth.

Less seriously affected acid sulfate soils belong to sulfic subgroups of Tropaquepts and Haplaquepts. These sulfic subgroups either have jarosite mottles and a pH of 3.5-4 in some layers within the 50-cm depth, or have jarosite mottles and a pH below 4 somewhere between a depth of 50 and 150 cm. The distinction between Tropaquepts and Haplaquepts is in the soil temperature regime. Sulfic Haplaquepts in Asia occur, roughly, north of the 17th parallel; Sulfic Tropaquepts — which are more widespread — are found where the soil temperature at the 50-cm depth differs by less than 5°C between the warmest and the coldest months.

The sulfic subgroups offer considerably more possibilities for agriculture than the Sulfaquepts. Over centuries, many Sulfaquepts have become sulfic subgroups after continuous weathering under progressively better drainage. In the center of the Bangkok plain in Thailand, more than 500,000 ha of acid sulfate soils have developed into Sulfic Tropaquepts. In those soils the pH of the surface soil is generally between 4 and 5 and the unosidized pyritic substratum is below the 100-cm depth.

In contrast, most of the acid sulfate soils in the Mekong delta, Vietnam, developed in sediments of similar age as those on the Bangkok plain, are oxidized and weathered to a shallower depth. The pyritic substratum there is generally within 1 m of the surface and the soils remain Typic Sulfaquepts. The retarded development of the Vietnam soils is due mainly to inhibited surface drainage. The poor drainage is also manifested by the presence of highly organic surface layers. In fact, some of the Vietnamese acid sulfate soils grade to the Sulfohemists, i.e. acid sulfate soils belonging to the Histosols order.

Whereas sulfic subgroups can develop from the pedogenetically younger and more acid Sulfaquepts, they may also form directly by oxidation of sediments with a relatively low (2%) pyrite content. An even lower pyrite content may cause an acidification to a pH not lower than 1-5 at any depth. This is common in many hydromorphic soils formed from recent coastal sediments in the tropics and subtropics. Those soils are mostly Typic Tropaquepts or Typic Haplaquepts and can be distinguished from their nonacid counterparts only at the family level in *Soil taxonomy.* They are sometimes designated as *para-acid sulfate soils* (Pons, 1973), but no precise diagnostic characteristics are applied.

Chemical constraints to rice growing on acid sulfate soils

Toxicities of acid sulfate soils for lowland rice are mainly from a high level of dissolved aluminum and perhaps also acidity *per se* in the early stages of submergence or, as in broadcast deep-water rice, during a dryland stage before flooding (Fig. 9). Excess iron is harmful in young acid sulfate soils after reduction. Additional growth-inhibiting factors are excess electrolyte, high carbon dioxide concentrations, and, especially in the older acid sulfate soils, low availability of phosphate (Ponnamperuma et al., 1973). Dissolved aluminum released from aluminum silicate at low pH is toxic to rice seedlings if the aluminum concentration exceeds 1 to 2 mg/liter. The concentration of aluminum in the soil solution of acid sulfate soils is about 1 mg/liter at pH 4.8 and changes roughly by a factor 10 for every unit change in pH, increasing with acidity and decreasing when the pH goes up (van Breemen, 1973). The surface horizons of most acid sulfate soils have a pH between 3.5 and 4.5 when not flooded, and thus contain a harmful concentration of soluble aluminum. But soil reduction after flooding increases the pH, sometimes to 6 or 6.5, making aluminum toxicity only temporary in submerged acid sulfate soils, and, in principle, circumventable by preflooding or late transplanting.

On the other hand, in many acid sulfate soils the pH rises slowly and remains well below 5 throughout the growing season so that high aluminum concentrations persist for a considerable time. The restricted increase in pH is due to

9. The orange discoloration of the broadcast rice in the center of this rice field on acid sulfate soils of the Bangkok plain, Thailand, is due to aluminum toxicity and phosphate deficiency during the dryland stage (before flooding).

limited reduction of ferric oxide to ferrous iron because the amount of easily reducible iron is small and conditions are unfavorable for the growth of anaerobic bacteria, and to a strong pH buffering of the soil in the low pH range.

In Sulfaquepts where the potentially acid substratum occurs at shallow depth, strong acidification due to oxidation in the dry season or during artificial drainage may cause the formation of efflorescences of readily soluble aluminum sulfate at the soil surface. Water that floods such land becomes strongly acid.

In Vietnam, pH values as low as 3.5 and aluminum concentrations between 10 and 70 mg/liter have been recorded in floodwater on the Plain of Reeds. Such lands will not grow rice, and crops on adjacent downstream lands are frequently damaged by the acid floodwater high in aluminum. Harmful surface water acidity has also been reported from Kalimantan, Indonesia. In contrast, surface water in areas with Sulfic Tropaquepts on the Bangkok plain normally has a pH above 4 and an aluminum concentration below 0.5 mg/liter.

Acid sulfate soils differ widely after flooding in their production of ferrous iron, which is strongly toxic for rice at concentrations above 500 mg/liter. In the surface horizons of flooded sulfic subgroups, dissolved ferrous iron does not normally reach toxic levels even if the soil pH remains below 5.5 throughout the flooding period. Toxic concentrations of ferrous iron seem to be typical for the younger Sulfaquepts. The difference may be the result of the presence of larger amounts of easily decomposable organic matter and of easily reducible ferric oxide in the younger soils. Where the pyritic substratum occurs at shallow depth (within 50 cm), reduction of ferric oxide by pyrite after flooding may also cause toxic levels of dissolved ferrous iron (van Breemen, 1976).

Suitability of acid sulfate soils for rice cultivation

It is difticult to generalize about suitability of acid sulfate soils and their predecessors, the potential acid sulfate soils, for rice growing in view of their widely different properties. In general, however, because flooding not only stops acidification by preventing pyrite oxidation but also tends to increase the pH, paddy rice is often one of the most suitable crops for such soils.

Potential acid sulfate soils will not acidify as long as the tidal effects are so strong as to prevent prolonged aeration. In most of such areas salinity is too high for rice cultivation. But along river banks where tides back up fresh water every day in the wet season, tidal swamp rice is possible. Tidal swamp rice is commonly grown in Indonesia (Kalimantan, Sumatra) and some West African countries (Sierra Leone, Guinea, Gambia), and traditional varieties sometimes produce 2 to 3 t/ha.

Reclamation of potentially acid saline swamps by diking to prevent seawater intrusion at high tides often leads to the formation of strongly acid Sulfaquepts and abandonment of the land, especially in areas with a pronounced dry season.

The Sulfaquepts include the most toxic acid sulfate soils, which are usually left uncultivated. Reclamation measures such as keeping the groundwater at shallow depth in the dry season, plus leaching and liming, are generally uneconomical for rice cultivation. When reclaiming such soils, one should realize that it often takes several years of improved land management before rice will grow at all.

The prospects for rice growing improve when acid sulfate soils have improved naturally by weathering and leaching over many years, as is the case with many soils belonging to sullic subgroups. In fact, most of these soils are used for wet-cultivated rice even though yields are generally low. Such acid sulfate soils can be made still more productive by proper fertilization and good cultural practices.

NUTRIENT DEFICIENCIES AND MINERAL TOXICITIES UNDER CERTAIN HYDROLOGICAL CONDITIONS

Rice commonly grows poorly on perennially wet soils. Rice plants suffer from a score of nutrient deficiencies on highly organic soils in their natural water-saturated state. Similar nutritional problems are encountered in wet mineral soils, particularly those in the Hydraquent great group (Chap. 4) composed of soft mud with a high water content. Often, local poor growth of rice is associated with strongly deficient drainage. In the valleys of Sri Lanka's wet zone, for example, rice in spots that are wet most of the year (Madakumbura) suffers more from phosphorus deficiency than rice in adjacent, better-drained fields.

The negative effect of prolonged and complete waterlogging on crop performance is demonstrated by alleviating such conditions. Improvement of drainage, even temporary, will cause most nutritional disorders to diminish or disappear.

In organic soils, improved drainage probably increases mineralization of organically bound nutrients. In mineral soils, zinc and, sometimes, copper may become more available upon drainage (Ponnamperuma, 1976).

Prolonged water saturation leading to these kinds of problems is observed either in closed depressions in fluxial rice lands (intermittent lakes) or in phreatic rice lands with upwelling due to interflow. Interflow also strongly aggravates iron toxicity in rice grown on sandy soils and receiving groundwater from adjacent upland areas with strongly weathered soils as in Sri Lanka, India, and many West African countries.

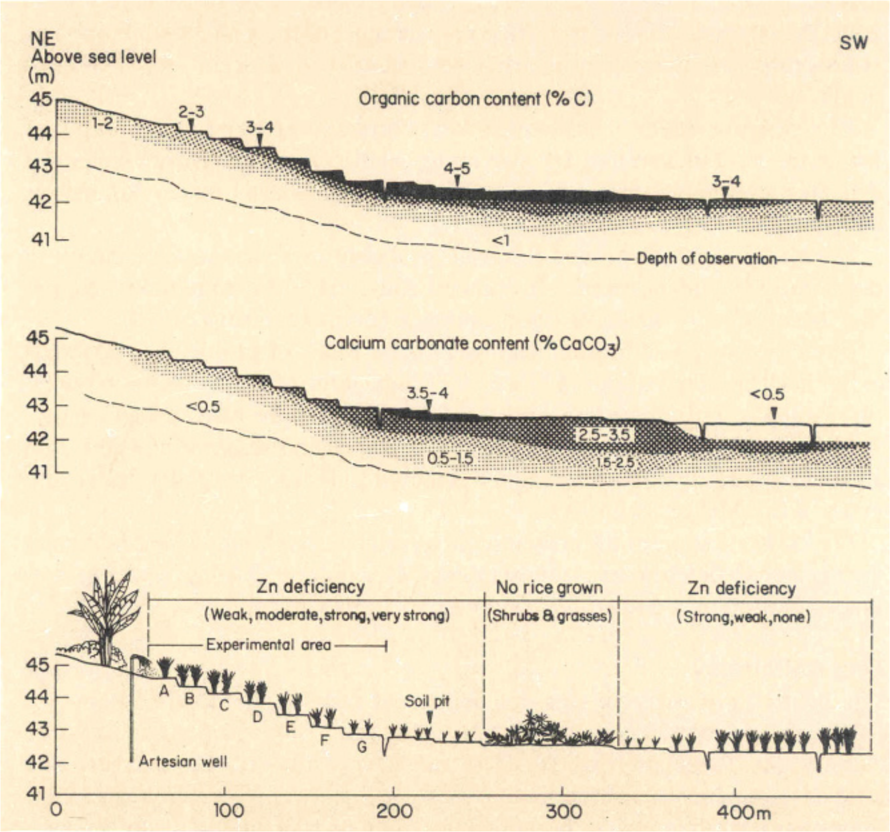
We illustrate some of the principles involved by describing two cases in more detail: zinc deficiency on a toposequence of soils near Tiaong, Quezon province, Philippines, and iron toxicity in Sri Lanka and Nigeria.

Zinc deficiency

One of the most severely zinc-deficient areas used for field experiments by IRRI is a toposequence on the gently sloping foot slope of a young inactive volcano, Mt. Banahaw (Fig. 10). The soils have a silty clay-loam texture and were developed in water-saturated pyroclastic materials. Drainage varies from somewhat poor in the upper part of the toposequence to poor in the lower part. The poor drainage is due to perennial upwelling of shallow artesian water, as evidenced by an artesian well (sunk to only 3 m below the soil surface) at the high end of the toposequence. The poor drainage is reflected by the profile morphology. The soils show gray, greenish-gray, and black colors without any brown ferric oxide mottles within the 180-cm depth (see Chap. 4, Fig.,2). In the lower part of the toposequence the soils often have a low bearing capacity because of a low degree of physical ripening.

The upwelling water is high in magnesium and calcium bicarbonate and in carbon dioxide. As the artesian water rises to the surface, carbon dioxide is lost to the atmosphere, causing a rise in pH, which favors formation of calcium-magnesium carbonate. The strongest accumulation of carbonate, partly as mollusk shells, is where upwelling is strongest and water saturation is most prolonged. Organic matter is similarly distributed.

The severity of zinc deficiency is also strongly correlated with the intensity of upwelling, but not with pH (7.8–8.0 in all air-dried, surface-soil samples) or with extracted zinc (Fig. 10). Without adding zinc, farmers obtain yields of 200 kg/ha or less in the most severely affected areas. Application of zinc and



10. Zinc deficiency in rice, hydrology, and distribution of calcium carbonate and organic carbon in soils of a toposequence near Tiaong, Quezon, Philippines.

good management result in yields as high as 5 t/ha. At the lower end of the toposequence farmers have drained the land through narrow ditches. This has a dramatic positive effect on rice growth, to the extent that no zinc deficiency symptoms are seen in areas where plants hardly grew before drainage. The low contents of calcium carbonate and organic matter in those fields may be due to decalcification and better æration after drainage.

The effect of drainage proves that the zinc deficiency is induced and not due mainly to low zinc content. At least four factors known to contribute to induced zinc deficiency play a role in the Tiaong toposequence: prolonged waterlogging, high dissolved bicarbonate, high magnesium, and high pH (Castro, 1977). The Tiaong toposequence is exceptional in that in the most severely affected parts all those factors act simultaneously.

In some other areas in the Philippines we observed zinc deficiency in noncalcareous, and sometimes even acidic (pH 5–6 when air dried), soils that are perennially water saturated because of interflow or upwelling. Although most interflow areas with zinc deficiency are fairly small, upwelling from artesian aquifers has been observed over hundreds of hectares of bottomland adjacent to mountainous areas as near Butuan, Agusan del Norte province, Philippines. All these poorly drained zinc-deficient soils are reduced throughout, i.e. they show no brown mottles of ferric oxides, in at least the upper 40–100 cm. Such a profile morphology, typical of Aquents (mostly Tropaquents or Hydraquents), signals zinc deficiency.

In calcareous soils, prolonged flooding associated with upwelling is not necessary to induce zinc deficiency. Yet in calcareous soils, as in northern India, the disorder is more severe in the most poorly drained parts of a certain area (Tanaka and Yoshida, 1970). Therefore, the degree of zinc deficiency is often correlated with small variations in flooding regime due to variations in microtopography (Fig. 11) or to the proximity of drains and bunds (Fig. 12).

11. The correlation of zinc deficiency with variations in flooding regime is seen in this rice field. Rice plants are most severely affected in the slightly lower spots where flooding is most prolonged.

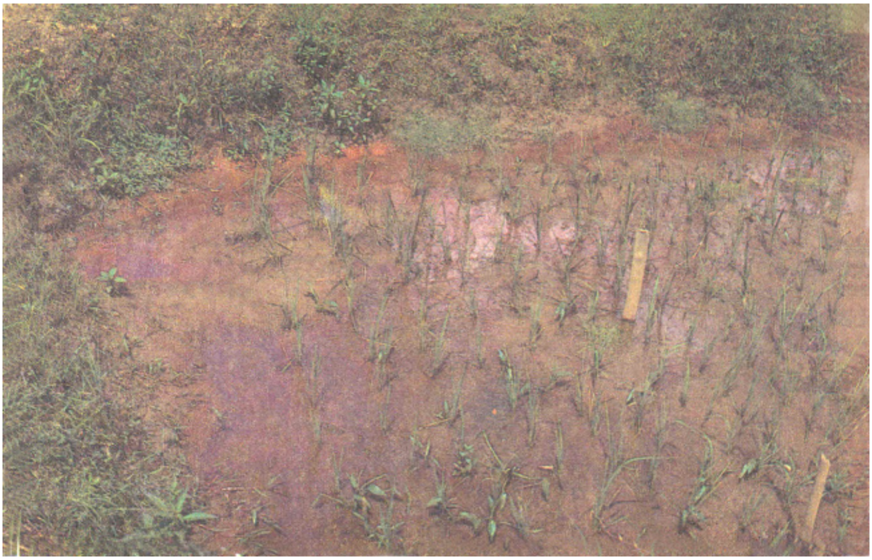
12. Zinc deficiency delays maturity of the rice plant. Rice near the bunds and drains in this field is more mature (yellow color) than that in the poorer drained interior of the field where zinc availability is lower.

The influence of hydrologic factors on zinc deficiency becomes less when the deficiency is practically absolute, i.e. when soils are low in total zinc, as in the highly weathered acid soils of South America. But there also, flooding and the associated increase in pH further lower the availability of the small amount of zinc present in the soil (Sanchez, 1976).

Iron toxicity

Rice suffers from iron toxicity and generally shows a purplish-brown or orange discoloration of the leaves (bronzing) if dissolved iron in the rooting medium exceeds 300 to 500 ppm. In soils with low nutrient levels (especially of potassium and phosphorus), or with respiration inhibitors such as hydrogen and ferrous iron, a concentration of iron as low as 30 ppm may be toxic.

Iron toxicity has been observed only in flooded soils, with a pH below 6.5, but which had a pH below 5 while aerobic. In young acid sulfate soils (Sulfaquepts), which often show dissolved iron concentrations exceeding 500 ppm for prolonged periods, iron toxicity occurs even if plants are adequately nourished. But in most other soils iron toxicity is normally associated with nutrient deficiencies and sometimes with hydrogen sulfide toxicity. The best studied examples of iron-toxic soils are in inland valleys of the low-country wee zone of Sri Lanka. There, in poor sandy- to coarse-loamy soils (Tropaquents, Fluvaquents, and Hydraquents) iron toxicity is closely correlated with upwelling of interflow water from adjacent highlands with Plinthudults.

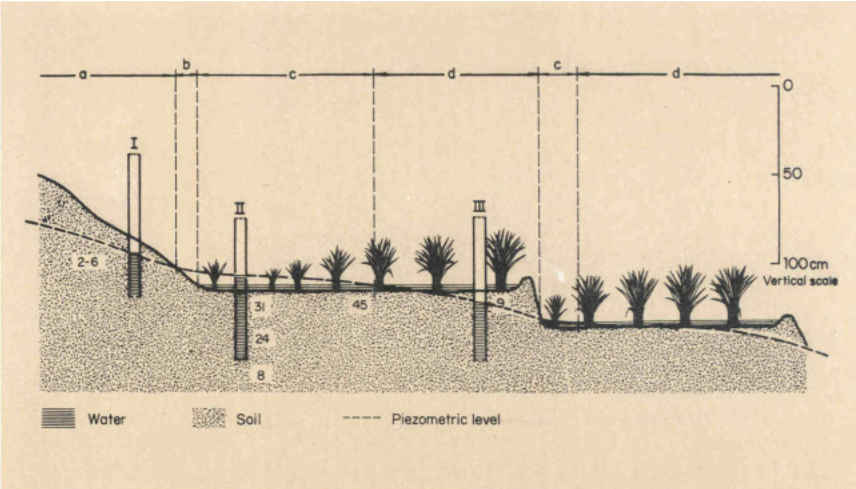


13. Scum of ferric hydroxide shows in the corner of this rice field in Sri Lanka. The appearance of ferric hydroxide is associated with upwelling or interflow from the higher area to the left of the paddy.

Upwelling sites, both in paddy fields and in adjacent upland soils, are often conspicuously covered with a scum of brown ferric hydroxides, formed by oxidation of ferrous iron carried upward by the water (Fig. 13). In three cases studied in some detail (two in Sri Lanka, one in Nigeria) the levels of ferrous iron in the interflow water itself were too low (1–10 ppm) to cause iron toxicity. But iron concentrations in the root zones of affected plants were distinctly higher (30–50 ppm). This is illustrated schematically in Figure 14, which is based on actual measurements at Padukka, Sri Lanka. The relatively low levels of dissolved iron in the root zone indicate that iron toxicity exists mainly by virtue of low levels of other nutrients and perhaps is aggravated by harmful substances such as hydrogen sulfide.

Interflow may have aggravated iron toxicity in several ways:

- by depleting the soil of nutrients, particularly potassium;
- by preventing the formation of a thin oxidized surface layer, which is present in most flooded soils, and thus hampering the establishment of a superficial root system that strongly depends on the presence of oxygen (poor development of the superficial root system of rice plants was observed in interflow zones at the International Institute of Tropical Agriculture, Nigeria); and
- by conveying dissolved ferrous iron faster than it can be inactivated by oxidizing roots, so that ferrous iron concentration becomes relatively high immediately adjacent to roots.



14. Hydrology of rice paddies in valleys in the low-country wet zone of Sri Lanka, illustrated by piezometer levels: *a* = upland; *b* = lateral seepage; *c* = upwelling zone with affected plants; *d* = percolation zone with healthy plants. Figures indicate concentrations of dissolved ferrous iron in interstitial water at various depths.

We point out, however, that iron toxicity can exist even if interflow is stopped artificially, e.g. by placing the soil in pots. But the disorder is normally much less severe in such cases.

Situations similar to those in Sri Lanka are also common in Orissa and Kerala states, India, and in many West African countries.

Whereas bunded and leveled fields are typical for Asia, rice is grown mainly on naturally sloping phreatic land in West Africa. Under these particular conditions, the intensity of the interflow, the concentration of dissolved ferrous iron, and the severity of bronzing in rice vary not only with time (in function of variation in rainfall periods of heavy rain) but also with location.

CHAPTER 7

Elements for evaluation of land for rice growing

THE TERM *LAND* is defined here as a specific area of the earth surface with characteristics that embrace all reasonably stable or predictably cyclic attributes related to the atmosphere, the soil, topography and hydrology, the plant and animal population, and the results of human activity (FAO, 1976). The totality of these attributes, rather than a single or a few selected ones, determines the inherent quality of a given tract of land for a given type of use.

LAND AND LAND QUALITIES

We are primarily interested in land qualities for rice, but we also include land qualities for rice-based cropping systems that include other crops grown on the same tract of land. A wide spectrum of attributes or land qualities should be examined when evaluating the inherent quality of a tract of land for rice cultivation.

For example, clayey soils are said to be superior to coarse loamy or sandy soils for rice growing. As indicated in Chapter 6, this statement often holds true, but it can by no means be generalized. In terms of soil attributes, for instance, clayey acid sulfate soils may not be desirable for rice cultivation. The same is true for clayey soils with other inherent soil restraints such as alkalinity. Very fine clayey soils may be difficult to cultivate, and clayey soils with a predominantly kaolinitic clay mineralogy may puddle unfavorably in paddy land or have a low water-holding capacity in pluvial rice land.

Clayey soils may occur in a poorly drained and continuously reduced state; they may be of little value unless artificially drained. In valleys they may be subject to flash floods, which lowers their suitability for highly productive, short-straw rice varieties. Clayey soils in many monsoonal river plains have different seasonal values — they are more productive with dry-season irrigation than with natural river flooding in the rainy season.

Thus, the single attribute of soil texture is in no way sufficient for evaluation of the actual or potential production capability of a given tract of land. Evaluation must be based on the measurement and study of the set of attributes of the land under study, and on the determination of the influence of each attribute, singly or in combination, on crop performance.

LAND QUALITIES AS RELATED TO RICE CROP PERFORMANCE

Land qualities, as defined and listed in *FAO Soils Bulletin No. 32* (FAO, 1976), serve as guidelines for the determination of the physical suitability of a given tract of land for rice.

The qualities most relevant for rice growing are

- moisture availability,
- oxygen availability in the root zone,
- nutrient availability,
- toxicity of soil and water,
- salinity and alkalinity,
- flooding hazards,
- workability and terrain factors,
- resistance to erosion, and
- day length and climate.

Moisture availability

As noted in Chapter 4, the availability of water is extremely important to the performance of rice. Lack of water during the growth cycle rapidly becomes a production-limiting factor, whereas water saturation of the root zone and shallow standing water on the soil surface are usually positive factors.

For *pluvial* rice land, moisture availability in the root zone is determined by effective rainfall — rainfall not lost by runoff or by rapid percolation — and by the effective water-holding capacity of the soil. Determination of these two parameters is, therefore, important in the evaluation of actual or prospective pluvial rice lands. Estimated rainfall requirements for growing pluvial rice are given in Chapter 3. It is noted that at a total annual rainfall of more than 1,600 mm, water availability is generally acceptable in pluvial rice lands of the intertropical zone except for soils with a low available water-holding capacity.

At annual rainfall of less than 1,600 mm, distribution and regularity play an increasingly important role. For most tropical soils with low water-holding capacity, drought for as little as 8–12 days during critical stages of the growing season (mainly from tillering to ripening) depresses yields and may increase disease incidence (Moormann et al., 1977).

With low rainfall, and especially with an irregular rainfall pattern, water-holding capacity becomes of major importance. With a given clay mineralogy the water held between the conventional limits of permanent wilting point and field capacity is positively correlated with the clay content. Hence, rice grown on the more clayey soils will better withstand drought periods. Visible damaging drought stress is delayed compared with that in soils of the sandy and coarse loamy families. Observations indicate that rice on sandy or coarse loamy soils is more than twice as drought susceptible as rice on fine loamy soils. On soils belonging to clayey families, water for the crop remains available during even longer drought periods. An exception is many (clayey) Oxisols, which act like sandy soils in view of their strong aggregation of clay particles (pseudo sand) (van Wambeke, 1975; Wolf, 1975). Pluvial rice on Oxisols is drought stressed rapidly after short rainless periods, even when the clay content of the root zone is 60% or higher.

The clay mineralogy of the soil material in the rooting zone is also important in areas with low and unreliable rainfall. The water-holding capacity of purely kaolinitic soil materials is considerably lower than that of materials that contain increasing contents of 2:1 lattice clays, more specifically montmorillonite (Moormann and Kang, 1978). A similar higher availability of useful water can be found in soils containing amorphous allophane; such soils are mainly Andepts.

The role of organic matter in water availability is much harder to define. The relative importance of organic matter is restricted in soils with favorable texture, favorable clay mineralogy, or both. But retention of useful water by the organic matter fraction becomes critical on sandy to loamy soils in the more marginal rainfall areas, and soils with high organic matter content are less susceptible to drought. Because organic matter also has other functions, its specific influence on water availability in pluvial rice lands is difficult to quantify. Observations of pluvial rice lands in Nigeria indicate that rice on freshly cleared forest land suffers less drought than rice on similar lands that have been cultivated for several years and where the organic matter content in the root zone has dropped drastically from its high preclearing value.

Moisture availability also depends on management. Crusting of soils decreases surface permeability and, hence, the moisture available in the root zone. Systems of mulching, or minimum or zero tillage, have the opposite effect besides diminishing erosion hazards. By far the most widespread management method to improve moisture availability is bunding and leveling to create pluvial-anthraquic rice lands. The end effect is increased effectiveness of rainfall through diminished runoff. Puddling also decreases percolation losses of moisture below the rooting zone, although less effect from puddling is expected in soils rapidly permeable throughout, e.g. Oxisols and the deep sandy families of other soil taxa.

Determination of the land quality *moisture availability* in pluvial rice lands, therefore, calls for observation and measurements, if possible, of

- rainfall and rainfall distribution;
- water-holding capacity of the soil in the rooting zone as determined mainly by texture and clay mineralogy, and to a lesser extent by organic matter content;
- losses to be expected from runoff and percolation below the root zone, the latter largely determined by the genetic soil taxon and the textural profile; and
- soil and land management factors, which are important for water retention.

For *phreatic* and *fluxial* rice lands the determinants of effective rainfall and water-holding characteristics of the soil, although still important, are partially or totally superseded by moisture available from an outside source as groundwater, surface water, or both.

The fact that rice land is phreatic or fluxial does not guarantee sufficient moisture. The amounts and regularity of the supply of interflow and surface water to the rooting zone and the movement of groundwater depend to a considerable extent on climate. Interflow water availability follows the rainfall pattern of the immediate groundwater catchment area (see Chap. 3). Fluxial water availability depends on local weather, or in the case of larger river valley systems, on weather in the upper catchment area, which is often a considerable distance from the land for which this particular land quality is to be determined. In years with low rainfall, therefore, the surfaces successfully planted to rice are much smaller than in high-rainfall years. A similar pattern may be observed with anthraquic conditions — bunded and leveled paddy fields— where no irrigation water is available. In northeastern Thailand, for example, where rice fields in the gently sloping valleys range from slightly to distinctly phreatic to eventually fluxial in the lowest position, the relation to rainfall and rainfall pattern is particularly clear. In dry years or in, years when rains are delayed, the upper fields are not planted because moisture is lacking. But in wetter years, entire valleys are planted. Unseasonal drought may, however, often affect yields along the whole toposequence. Similar topography-rainfall relationships regarding water availability in paddy fields in the Philippines are discussed in Chapter 3.

Moisture availability is optimal with flooding regime 4 (irrigated rice lands). This flooding regime occurs in irrigated areas where water is plentiful or in areas with sufficient rainfall to feed even the less modern irrigation systems, such as the terraces in Banaue, Philippines, or the *sawahs* on the volcano slopes in the high-rainfall areas of Java.

But water is not always available in rice lands served by irrigation schemes. Often the location of land-in relation to the distribution system is important. IRRI research in the Peñaranda River Irrigation System, Central Luzon. Philippines (Tabbal and Wickham, 1976), determined that the number of days when rice plants suffered drought stress in irrigated paddy fields was a function of several location, hydrologic, and management factors that were interrelated and sometimes overlapping. The most important factors affecting drought incidence were location of the fields in respect to the lateral and sublateral canals and the overland distance from the turn-in point to the field.

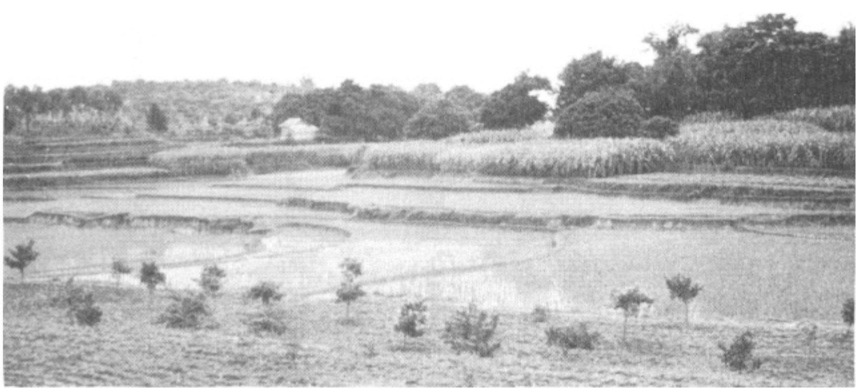
So, the land quality *moisture availability* varies from place to place and from year to year, even in irrigated areas. This variability must, therefore, be taken into account when evaluating the particular land quality for the different parts of an irrigated area. Available moisture in phreatic and fluxial rice land, whether irrigated or nonirrigated, depends in the final analysis on the same factors as in pluvial rice lands, although to a lesser degree. Where sufficient outside water, regardless of source, can reach the rice fields, moisture availability is optimum and yields will not be depressed due to moisture stress. But we emphasize that such ideal conditions are found only in a small part of the world's total rice hectarage — in the zones with high and dependable rainfall — and in some arid zones with dependable sources of outside water.

Oxygen availability in the root zone

The land quality *oxygen availability in the root zone* is of little importance to the rice plant, which adapts to a reduced soil condition. Indirectly, complete reduction — and absence of oxygen — can develop deficiencies and toxicities, and thus adversely affect rice productivity. That normally is not the case for rice land ærated between rice crops but it may play a role in, and hence diminish the value of, land that is continuously saturated, such as in closed depressions of zones with a udic moisture regime and in parts of a landscape subject to upwelling of interflow water.

Oxygen availability in the root zone is of great importance in multiple cropping systems where rice is grown in sequence with other crops. Availability of oxygen must be considered when evaluating land for such systems.

Not all rice land can be multiple cropped. Many river-basin soils on the major plains of Southeast Asia are frequently not sufficiently ærated in the dry season to permit successful upland crops unless the soils are artificially drained or ridged. In other somewhat better ærated soils, the choice and timing of crops other than rice are often limited. Crops such as soybean may withstand partial waterlogging or even temporary inundation after germination, but crops such as corn are strongly affected by temporary waterlogging. Rainfed and irrigated paddies on the higher elevations can usually be drained easily, permitting cultivation of dryland crops any time that water is sufficiently available (Fig. 1).



1. Ease of drainage governs the use of rice-growing soils for dryland crops. On the high area in this rice-cropped inland valley in the People's Republic of China, a row crop is interplanted among fruit trees on the sloping land (foreground) and a dryland cereal crop is on the drained paddies (background). (Photo by Graham Johnson, University of British Columbia)

Reflecting oxygen availability in the root zone throughout the year, the land-use classification system of the broad river plains of central Thailand recognizes the following classes:

- Land that should not be used for rice growing — free drainage and restricted water availability.
- Land that can be used either for rice growing or for dryland crops — reasonably free drainage, but possibilities for impounding water on puddled rice lands.
- Land that can be used for a rotation of one rice crop in the wet season and dryland crops with supplementary irrigation in the dry season. Saturation of the root zone in the rainy season precludes the use of such land for dryland crops during that period, unless the land is ridged and thoroughly drained.
- Land that can be used for two rice crops, but is too poorly drained for all but a few dryland crops.
- Land that is usable for one rice crop and unsuited for dryland crops — pertains to the lowest and most deeply flooded lands where the flooding pattern determines an exclusive suitability for rice growing.

Nutrient availability

Although the land quality *nutrient availability* is of major importance for the productivity of a given rice land, it is predictable only at low levels of management, i.e. when no fertilizers are applied. In the opposite case, when correctly fertilized, soils that have an inherent low fertility can give high production, provided there are no other production-limiting factors. Fertility management, combined with advanced plant-, soil-, and water-management techniques (improved varieties, irrigation, etc.), is the key to the high productivity of rice land in the temperate regions; the same trend of increased productivity is observable on the better rice land in the intertropical zones.

The lower the level of fertility management of rice land, the more important is inherent nutrient availability as a land quality to evaluate in such lands. In the broad view, this land quality is related to the physical and chemical characteristics of taxonomic units. For instance, Inceptisols on young river sediments and Mollisols on volcanic materials have a higher available-nutrient status than Ultisols.

In a classical study on the relationship between soil map units and yield levels of nonfertilized paddy rice in East-central Java. Hauser and Sadikin (1956) found that the dominant factors in productivity were parent material and the state of weathering of that material. Both factors can be related to the land quality of nutrient availability. Table 1 gives relationships between average yields, parent material, and degree of weathering for part of the area studied.

From this study and from other observations, it seems apparent that the land

Table 1. Paddy yields versus parent materials and stage of weathering on volcanic parent material, Java, Indonesia.[a]

Basic (Nephritic) materials	Av yields (t/ha)	Intermediate (Andesitic) materials
	2.0	—strongly weathered soils
	2.5	—medium weathered soils
strongly weathered soils—	2.6	
	3.3	—least weathered soils
medium weathered soils—	3.6	

[a] Source: Hauser and Sadikin, 1956.

quality of availability of nutrients in unfertilized soils often cuts across the taxonomic units, even when separated at the family or series level.

In pluvial rice lands under shifting cultivation, nutrient availability is a transient characteristic. It may be high the first year after clearing, but diminishes in subsequent years, leading to periodic shifts to new lands. On the inherently fertile soils rice will grow for several years, but on soils of lower inherent fertility, only one or two consecutive rice crops can be grown unless the land is fertilized.

Within the framework of this book, it is impossible to discuss all of the fertility aspects and fertility management of rice. We do, however, observe the relationships between the major and minor elements required for the nutrition of rice plants, and specific land types in the sense of *FAO Soils Bulletin No. 32.*

NITROGEN. Lack of nitrogen is virtually always a production-limiting factor. In pluvial rice lands, nitrogen is provided mainly in the organic form, which becomes available from decomposition of organic matter after land clearing. The amount of nitrogen available after clearing is a function of the type of vegetation, the biomass available, and, indirectly, of the taxonomic soil unit because it influences the development of the secondary vegetation in shifting agriculture systems. The customary bush burning by the shifting cultivator does not always volatilize all nitrogen in the axial parts of the vegetation. In the more moist climates much of the nitrogen is found in the ash and in incompletely burned vegetation, thus providing sufficient nitrogen for a first rice crop (Sanchez, 1976). In consecutive growing seasons, lack of nitrogen rapidly becomes a crop-limiting factor.

Burning of the rice straw and stubble, frequently done in aquatic rice fields during the dry season, does not cause complete loss of nitrogen for the same reason. Moreover, the nitrogen that remains in the rice straw ash after burning is more readily available than that from unburned straw when the straw is incorporated into the soils of paddy lands.

Submerging the soil enhances the supply of nitrogen. This is mainly due to increased biological nitrogen fixation, which can take place both in the surface water and in the reduced soil, and to a more rapid accumulation of inorganic nitrogen by mineralization of organic nitrogen. The permanent cropping of aquatic rice land in Asia for many centuries without any application of nitrogen from an outside source has been possible mainly because of fixation of atmospheric nitrogen.

Apparently, the intensity of nitrogen fixation varies with the type of land but no reliable quantitative data are known. On nonfertilized clayey Inceptisols on marine and river sediments of Thailand in pluvial anthraquic land, typical rice yields are 1.5 to 2.4 t/ha. On the sandy, kaolinitic soils of northeastern Thailand, typical yields are considerably lower - in the order of 0.7 to 1.2 t/ha. Although factors other than nitrogen availability are more important in this differentiation of the *natural* yield potential, it should be noted that the export of nitrogen in the harvested rice is considerably greater in the first mentioned area, but does not lead to exhaustion of nitrogen from natural sources.

The efficiency of applied fertilizer nitrogen varies with land type and management, and is decreased by losses of various kinds.

Ammonium is often more mobile in a reduced than in an ærated soil, and appreciable amounts of applied ammonium are leached where percolation or upwelling takes place in paddy fields. Puddling greatly diminishes such losses in clayey, fine silty, and fine loamy soils. No actual figures have been reported, probably because of the technical difficulties of measuring such losses in flooded soils.

Alternate oxidation and reduction greatly enhance the loss of applied nitrogen, but not necessarily of soil nitrogen, by nitrification and denitrification. In this respect the flooding regime, and thus the land quality of moisture availability are of particular relevance. Low pH hampers the activity of nitrifying and denitrifying microbes and such losses are small in acid soils (ærobic pH below 5).

Appreciable nitrogen losses by ammonia volatilization take place only when bases are available to keep the pH above 7 to 7.5. In flooded soils such pH values may readily develop in the surface water due to photosynthesis by algae. Volatilization losses from ammonium sulfate are negligible in poorly mineralized water or in rainwater, but may exceed 50% of applied nitrogen in calcareous soils irrigated with alkaline water. But nitrogen from urea, which is itself basic in reaction, may be lost by ammonium volatilization even if the soil and surface water are relatively low in bases.

Good management such as proper timing and placement of fertilizer, use of slow-release fertilizers, and sound irrigation practices considerably curtail the losses mentioned above and make this land quality less important.

Even with high fertilizer rates and good management, however, 50 to 75% of the nitrogen taken up by the rice crop from a flooded soil is usually soil nitrogen (Broadbent, 1977). This suggests that the amount of nitrogen mineralized and the pattern of mineralization of soil nitrogen are important not only at low but also at high management levels. This is corroborated by practice, at least in Japan and China, where application of compost in addition to fertilizer nitrogen is considered necessary to achieve high rice yields and is presumably related to the favorable nitrogen-supply characteristics of the organic material (Tanaka, 1978).

Nitrogen mineralization patterns strongly depend on tillage history and weather and on the kind and quantity of applied organic material. But certain inherent soil properties such as pH, cation exchange capacity, and clay mineralogy are at least as important. For example, the presence of amorphous constituents (allophane) and 2:l lattice clay contributes to a favorable, i.e. moderately slow but steady, release of ammonium in flooded soils (Yoshino and Dei, 1977; Shiga and Ventura, 1976).

Nitrogen availability may be low in permanently or semipermanently waterlogged rice lands. Under such conditions mineralization of soil nitrogen is restricted and nitrogen deficiency can occur, even when the nitrogen content of the soil is high (IRRI, 1978).

PHOSPHORUS. The availability of phosphorus in unfertilized soils depends on several factors; the more important are the phosphates in the soil and the biomass available for the nutrition of the rice plant, phosphates retention or fixation characteristics of the soil, and management of soil and water.

Soils that are rich in sesquioxides, such as Andepts that contain allophane, and ferric oxide-rich Oxisols and Ultisols, often have a high retention or fixation of phosphates. Phosphorus deficieny is a main production-limiting factor on such soils, whether pluvial, phreatic, or fluxial, and high doses of phosphorus fertilizers are required.

The availability of phosphorus is sometimes lower in poorly drained fields than in adjacent better drained fields, as in the midcountry wet zone of Sri Lanka. But phosphorus availability is usually better in flooded than in dryland soils, mainly because phosphate occluded in and absorbed on ferric oxide is released during reduction, as is phosphate in ferric phosphate.

But in the past, little of the phosphate extracted by successive crops has generally been replenished, and low availability of soil phosphorus is a major production-limiting factor in most rice lands of the world.

POTASSIUM. At the low management level of most rice lands, the level of available potassium is usually sufficient. Sources of potassium for the rice plant are exchangeable potassium in clay minerals, mainly biotite, hydrous mica, and illite. More slowly available potassium is liberated during the breakdown of feldspar (orthoclase) and mica. In rice lands flooded with water from outside sources, some potassium is usually available from floodwater or irrigation water.

Available potassium may be below the critical level required for optimum rice growth on the most weathered soils such as Oxisols, on many Ultisols with low cation exchange capacity, and on quartzitic sands (Psammaquents, Quartzipsamments, Spodosols). At the same time, however, other nutrients may be limiting on such soils, making lack of available potassium one of several limiting factors.

OTHER NUTRIENTS. At low levels of management, and especially where rice is flooded, other essential plant nutrients are not generally in short supply. However, zinc deficiency may locally limit production in unfertilized rice land.

Calcium contents are low in the most strongly leached soils and in some soils derived from serpentinite parent materials, while calcium availability is strongly suppressed in highly alkaline soils.

Sulfur is usually present in sufficient quantities, especially in aquatic rice lands, but it may be limiting in pluvial rice lands.

Iron is rarely in short supply in aquatic rice fields, but in pluvial rice fields, iron deficiency may occur in calcareous soils or in soils where iron oxides occur exclusively in a highly crystalline, insoluble form.

Copper deficiency in rice is known to occur on soils where the surface has a high organic matter content.

Silica is considered essential for normal growth of the rice plant. Under most conditions, the natural silica supply is sufficient, but on low pH soils consisting mainly of quartz sand and on organic soils, silica may be below the critical level.

CLASSIFICATION OF SOIL FERTILITY CAPABILITY. Classifications that provide the means to estimate and evaluate the land quality *availability of plant nutrients* for rice lands are being tested. The system proposed by Kawaguchi and Kyuma (1977) for *paddy soils* is based on the statistical analysis of 29 variables obtained by soil analysis. These variables, which are partly interdependent, have been grouped in three sets of characteristics related, respectively, to base status, to organic matter and nitrogen status, and to phosphorus status. Interpretation of these data leads, we feel, to a quantitative evaluation of soil fertility and an objective grading of soil samples. Although promising, the method is time-consuming and requires excellent laboratory facilities and standardized methods of analysis.

In South America, scientists from North Carolina State University, USA, together with soil scientists from various participating countries, have elaborated a fertility-capability soil classification system that groups taxonomic soil units into units of similar fertilizer response (Buol et al., 1975). The format of that classification system is outlined in Table 2. The system is not crop specific, and will require adaptation for the specific reaction of the rice crop to the parameters listed. The advantage of this approach is that most data can be gathered in the field or by careful interpretation of good soil maps, and it requires a relatively low analytical input.

Table 2–Fertility-capability soil classification system.

TYPE: Texture is average of plowed layer or 20 cm depth. whichever is shallower
S = sandy topsoils: loamy sands and sands (USDA).
L = loamy topsoils: <35% clay but not loamy sand or sand.
C = clayey topsoils: >35% clay.
O = organic soils: >30% O.M. to a depth of 50 cm or more.

SUBSTRATA TYPE: Used if textural change or hard root restricting layer is encountered within 50 cm.
S = sandy subsoil: texture as in type.
L = loamy subsoil: texture as in type.
C = clayey subsoil: texture as in type.
R = rock or other hard root restricting layer

CONDITION MODIFIERS: In plowed layer or 20 cm whichever is shallower, unless otherwise specified (*).

*g = (gley): mottles $\leq$ 2 chroma within 60 cm of surface and below all A horizons or saturated with H_2O for > 60 days in most years.
*d = (dry):ustic or xeric environment; dry > 60 consecutive days per year within 20–60 cm depth.
e = (low CEC): < 4 meq/100 soil by Σ bases + unbuffered Al.
< 7 meq/100 by Σcations at pH 7.
< 10 meq/100 soil by Σ cations + Al + H at pH 8.2.
*a = (Al toxic): > 60% Al saturation of CEC by (Σ bases and unbuffered Al) within 50 cm.
> 67% Al saturation of CEC by (Σ cations at pH 7) within 50 cm.
> 86% Al saturation of CEC by (Σ cations at pH 8.2) within 50 cm.
or pH < 5.0 in 1:1 H_2O except in organic soils.
*h = (acid): 10-60% Al saturation of CEC by (Σ bases and unbuffered Al) within 50 cm or pH in :1 H_2O between 5.0 and 6.0.
= (Fe-P fixation): % free Fe_2O_3/% clay; 0 2 or hues redder than 5 YR and granular structure.
< = (x-ray amorphous): pH > 10 in 1N NaF or positive to field NaF test or other indirect evidences of allophane dominance in clay fraction.
v = (Vertisol): very sticky plastic clay > 35% clay and > 50% of 2:1 expanding clays: COLE > 0.09. Severe topsoil shrinking and swelling.
*k = (K deficient): < 10% weatherable minerals in silt and sand fraction within 50 cm or exch. K < 0.20 meq/100 g or K < 2% of Σ of bases, if Σ of bases < 10 meq/100
*b = (carbonate): free $CaCo_2$ within 50 cm (fizzing with HCl) or pH > 7.3.
*s = (salinity): 4 mmho/cm of saturated extract at 25 C within 1 m.
*n = (sodic) > 15% Na saturation of CEC within 50 cm.
*c = (cat clay): pH in 1:1 H_2O is < 3.5 after drying, Jarosite mottles with hues 2.5Y or yellower and chromas 6 or more within 60 cm.

Source: Buol et al. (1975).

Toxicity of soil and water

The land quality *toxicity of soil and water* is expressed negatively. In most rice lands, toxicities do not exist so it is not necessary to take them into account when determining the potential of the land for rice cultivation. But in specific areas, either those already in use for rice or those considered for extension of rice land, toxicities often seriously limit optimum productivity.

The most important production-depressing toxicities were discussed in the previous chapter. They include toxicities caused by excess of ferrous iron, by high contents of soluble aluminum (as for instance in acid sulfate soils) and by growth-inhibiting organic acid, and sometimes by hydrogen sulfide in strongly reduced acid soils that are high in organic matter. With the exception of aluminum toxicity, the toxicities occur exclusively in aquatic rice lands. Pluvial rice may suffer from high levels of aluminum in very acid soils, such as some of the strongly leached Ultisols in high rainfall areas. There is a considerable varietal difference, however, and many of the rice varieties developed in nonacid or slightly acid soils are susceptible to aluminum toxicity in pluvial rice lands with a low surface soil pH where traditional varieties grow well.

For flooded soils, several soil toxicities are not native to the soil of the rice field itself but are related to a hydrological condition, e.g. upwelling by interflow, or flooding with highly acid surface water from acid sulfate soil areas. Such conditions cannot be evaluated and measured by simple analytical determinations, nor can they be predicted and measured in the fields in most cases. Evaluation of the potential for iron toxicity, for instance, often requires the study of the soils and hydrology of the entire area in which it occurs.

Because toxicities in aquatic rice land are so often related to soil or surface water, they vary mostly according to the dynamics of water. Thus, moderately acid soils in the range of acid sulfate soils may give reasonable yields if the soils remain reduced during rice growth. But temporary lack of water in dry years may cause oxidation of the surface soil, with accompanying acidification and aluminum toxicity.

The reverse situation may also be observed in the upstream parts of areas with acid sulfate soil, as in the deltas of the Mekong and the Chao Phraya rivers. There, good quality floodwater may enter the acid areas by natural flooding, or as in the Plain of' the Reeds in Vietnam, by canals dug for transportation. Rice grows reasonably well along such canals because the good-quality water suppresses or negates the toxicity.

These examples may indicate that simple measurements are rarely sufficient to evaluate this negative land quality. It is necessary to determine the dynamics of toxicity phenomena and their relation to the overall edaphic and hydrologic conditions of the landscapes in which they occur. This can only rarely be done by the classical methods of soil and land survey; continuous monitoring over several years is usually required. In the absence of such a monitoring program, failures of land development projects for rice are all too common.

Salinity and alkalinity

Relationships between the negative land qualities of salinity and alkalinity and the performance of rice were covered in Chapter 6. In general, it follows that land subject to salinity and alkalinity will improve under aquatic rice if sufficient fresh water is available. That practice diminishes the severity of salinity and alkalinity as a negative land quality for the rice crop.

But in some cases, simple bunding and leveling of land and availability of good quality water for impounding in the paddies are not sufficient. On land that is subject to salinity of marine origin, or especially where cyclonic disturbances cause periodic flooding with seawater, temporary salinization during critical stages of the rice crop can cause serious damage or crop failure. Rice land subjected to such periodic, often unpredictable, saltwater flooding is of lower inherent quality.

Salinity related to interflow and phreatic movement of saline groundwater is normally sufficiently depressed in aquatic rice lands to be of consequence. But where the hydrology of the catchment basin is greatly changed by the construction of water reservoirs for irrigation, this type of salinity may be a source of land deterioration, even in paddy fields that were previously nonsaline. The construction of tanks and larger reservoirs in northeast Thailand, for instance, has in certain cases led to the salinization of downstream paddy fields. A thorough knowledge of the dynamics of the phreatic saline groundwater is required for project formulation in areas of this nature.

Salinity becomes a severe limiting factor in areas with potential salinity and a dry climate when project planning includes rotation of wetland rice with dryland crops instead of exclusive rice cropping. Alternating a wet-season rice crop with a dry-season, irrigated, nonsubmerged crop may bring about severe salinization due to evaporative salt concentration in the surface layers when the potentially saline soil is kept moist during a period of high evapotranspiration. Sometimes the surface salt accumulation will affect even the subsequent rice crop. Land deterioration in such project areas is widespread, especially in monsoonal and semiarid parts of Asia.

Therefore, while the wish to grow crops that demand less water is understandable from a water-economy point of view, the loss of crop yields due to salinization may, and often does, negate the initial gains. In terms of land evaluation, it must be determined to what degree such lands, which are not saline under aquatic rice cultivation but are potentially saline under changes in land and water use, will be affected. The conclusion may well be that exclusive cropping of rice in aquatic conditions is the only alternative unless efficient drainage systems can be introduced.

Flooding hazard

Flooding, as a predictably cyclic phenomenon, is not normally a negative land quality for rice cultivation. Because rice is a semiaquatic plant, it is adapted to flooding and some varieties can withstand submergence of even a week or more. Moreover, varietal adaptation to various depths and durations of submergence largely eliminates hazards caused by flooding. Nevertheless, the land quality *flood hazard* may be a constraint to rice production or may even exclude land from rice growing.

The hazards of saline water inundation during cyclonic disturbances in certain coastal areas have already been mentioned. Often, the hazard is the salinity brought about by such inundations, rather than the floods themselves.

Nevertheless, such typhoonal coastal inundations may cause water to rise rapidly in the upstream deltas and river plains and lead to destruction of the rice crop if high water levels persist.

In general, rapidly rising floodwater is a hazard to rice cultivation, wherever it occurs. A rise of more than 15 to 20 cm/day may even kill floating rice varieties.

Short-duration flash floods in inland valleys occur in many areas during heavy rains in the catchment areas. Such flash floods rarely exclude the use of land for rice; nevertheless, they should be considered a hazard and a potential yield-depressing parameter. Serious flash floods will physically damage the local land and crop and require much effort and time to restore bunds and irrigation structures.

Therefore, while flooding per se is normally not a hazard to rice cultivation, it should be considered where rapidly rising floods may occur. The noncyclic and mostly unpredictable character of such floods constitutes the hazard to rice cultivation.

Land workability and terrain factors that affect mechanization

The land qualities *workability* and *terrain factors affecting mechanization,* which are listed separately in *FAO Soils Bulletin No. 32,* are sufficiently interrelated to discuss under one heading. Evaluation of the workability of land depends largely on the system of soil and water management used or being planned.

Land preparation and other operations, including weeding and harvesting, can be done by hand without specific restraints on most land types and most soils. Difficulties are encountered in stony and sloping lands, but these are only a fraction of the actual or potential rice land area. Problems exist in the preparation of boggy land with poor drainage because of poor trafficability throughout or during most of the year (see Fig. 3. Chap, 4).

Physical limitations for land preparation by hand are encountered on fine clay soils, e.g. Vertisols, in climates with a pronounced dry season. If mechanical action is not available such soils often must be laboriously prepared by hand (Fig. 2).

A first level of mechanization is the use of animal traction, mainly carabaos or cattle, for plowing and puddling, and transport of the crop from the field. Possible restraints are partly of the same nature as for hand operations - poor trafficability on boggy lands and high energy requirements on fine clay soils (mainly Vertisols) where the period during which land can be prepared is limited.

In pluvial rice lands where shifting cultivation (bush-fallow) is practiced, the condition of the land after clearing is usually not suitable for animal traction because of the presence of stumps and general unevenness of such land. The farming must be changed to make the land suitable for that level of mechanization or for more advanced systems.

Topographical restraints may be present, such as in terraced paddy fields on

2. Land preparation by hand turning of the clods in this paddy on a Vertisol in Ilocos Norte, Philippines, demonstrates the importance of workability as a land quality.

slopes steeper than 5%. For instance, no animal traction is used in the step-land *sawahs* of Java, or in similar areas elsewhere in Asia, even though animals are commonly used for various operations in adjacent paddy areas that are lower and flatter (Fig. 3).

A limiting factor regarding the use of animal traction may be the susceptibility of the animals to endemic pests and diseases. The presence of tsetse flies

3. No animal traction is possible on these narrow terraces in the Solo River Basin, Java. (FAO photo by F. Botts) that carry trypanosomiasis in the moister savanna and forest areas in Africa is an example of environmental restraints to animal mechanization. The carabao is, however, being successfully introduced for aquatic rice growing in the Amazon area of Brazil.

The introduction and use of mechanical power for operations related to land is a further level of mechanization. Curfs (1976) points out several categories of constraints to agricultural mechanization of rice cultivation, which are often interlinked. Many are related to technical, educational, economic, and social factors. We cover only physical and biological factors related to the land.

A second aspect discussed by Curfs is that there are clearly distinguishable levels of mechanization related to the land. They range from the use of simple two-wheeled tractors for land preparation to large-scale, fully mechanized rice farming, including land leveling, the use of large tractors, mechanical and chemical weed control, and harvesting with combines. For each sublevel of these types of mechanization, specific requirements regarding land conditions and water control are valid. For instance, for fully mechanized large-scale rice cultivation, larger consolidated and more or less flat tracts of land are required, with water control to assure optimum trafficability and accessibility at the time required for operation of heavy equipment. This type of mechanization is restricted mainly to wide alluvial plains and terraces, where drainage is either naturally satisfactory or can be artificially controlled. Fully mechanized pluvial rice also requires larger flat-to-gently undulating upland tracts that are completely stumped and smoothed.

Physical and biological constraints to simpler types of mechanization, such as the use of two-wheeled tractors or small four-wheeled tractors for land preparation and puddling, are similar to those for animal traction.

Therefore, it must be concluded that the land qualities of workability and trafficability in relation to mechanization are variable as regards the level and kind of mechanization introduced. Land characteristics that determine the possibilities for mechanization at an appropriate level pertain mainly to texture, presence or absence of stones or rocks, drainage conditions, bearing capacity of the surface and subsurface horizons, and slope.

The hard, coarse, blocky structure that occurs after drying of many puddled rice soils, plus the presence of a traffic pan, adversely affects the growth of dryland crops grown in rotation with rice, and thus limits the possibilities for rice-based cropping systems. Medium textured soils and soils high in organic matter have a better postflooding tilth than the fine textured soils. But traffic pans, which limit rooting and availability of water and nutrients for dryland crops, and which may cause ponding of water after heavy rains, are more strongly developed in medium- than in fine-textured soils.

Resistance to erosion

Erodibility of phreatic and fluxial rice lands is not normally a problem, even when rainfall or runoff is high. The main land characteristic that gives such lands a high resistance to erosion is their dominant situation in a flat or gently depressed topography where the scouring action of water is either nil or strongly diminished. Moreover, the technique of bunding and leveling, dominant in most rice areas of Asia with a discernible slope, diminishes erodibility of the land because of an increase in the length of the runoff flow system, and of the storage of excess water in individual fields.

Major floods in narrow, short river valleys and on alluvial fans may cause considerable damage by scouring action along the river banks. New channels may form, destroying sizable areas of rice land. Such destructive river erosion is most serious on rivers where the natural vegetation of the catchment uplands has been destroyed by pressure for more agricultural land.

Terracing of steep slopes can be done successfully only if the resistance to erosion is high (Fig. 4). Even so, on steep, terraced paddy lands — as in Banaue, Philippines, or on the steep volcanic slopes in Java — mass movement may cause slides that damage the land considerably. The intensity of land use is such, however, that the destroyed terraces are rapidly reconstructed.

Pluvial rice land that is nonbunded and nonleveled is subject to erosion depending on erodibility of the soils, erosivity of the rains, length and gradient of slope, and vegetative cover. Compared with other land-use types, the main variable is the vegetative cover, and that parameter is not favorable in the case of rice cultivation. Under pluvial conditions, rice is less competitive

4. The high resistance to erosion of deeply weathered sandstone and siltstone allows rice farmers in Ifugao province, Philippines, to carve their rice terraces out of steep land. (Photo by H.C. Conklin, Yale University) with weeds than most other crops and requires clean-weeded conditions. When rice is planted as a row crop, the vegetative cover on a field provides relatively little protection against erosion in the early stage of the crop cycle. The use of erodible land for monoculture pluvial rice often results in considerable sheet and rill erosion. This is the case in modern large-scale, dryland rice farming — as in West Africa — and in intensified shifting cultivation systems where population pressure leads to an overuse of sloping, erodible land. Extensive erosion is taking place, for example, on the steep foot slopes of valleys in the hilly terrains of continental Southeast Asia where the valleys alone can no longer feed the population, and unsuitable land has gone into rice monoculture. Similar signs of accelerated erosion are observed in the hilly lands of the rice belt of West Africa, e.g. in Sierra Leone and Guinea.

Land qualities related to day length and climate

Most of the land qualities related to *day length and climate* have been summarily mentioned in previous chapters, so we include no extensive discussion here. Variation in day length is not really a restraint for the rice crop in general, in view of the range of varieties that are not sensitive to photoperiod or that are adapted to specific day length variations during the growth cycle.

The same varietal adaptation and, to a lesser degree, management adaptation have been obtained for land qualities related to temperature regime and radiation energy, even though most land types with low, temperatures (mountainous areas) and low levels of solar radiation (cloudy equatorial areas) are less productive.

Humidity is normally not a factor that directly affects growth and performance of rice, but diseases are generally more prevalent and serious in humid than in dry areas. In monsoon climates, where rice is grown in both high and low humidity regimes, the disease factor is clearly observable and is one reason that the same varieties usually yield more when planted in the dry season. Low air humidity, paired with desiccating high winds, was found to cause partial or total sterility in irrigated rice in the Senegal River valley in years with strong dry winds from the Sahara.

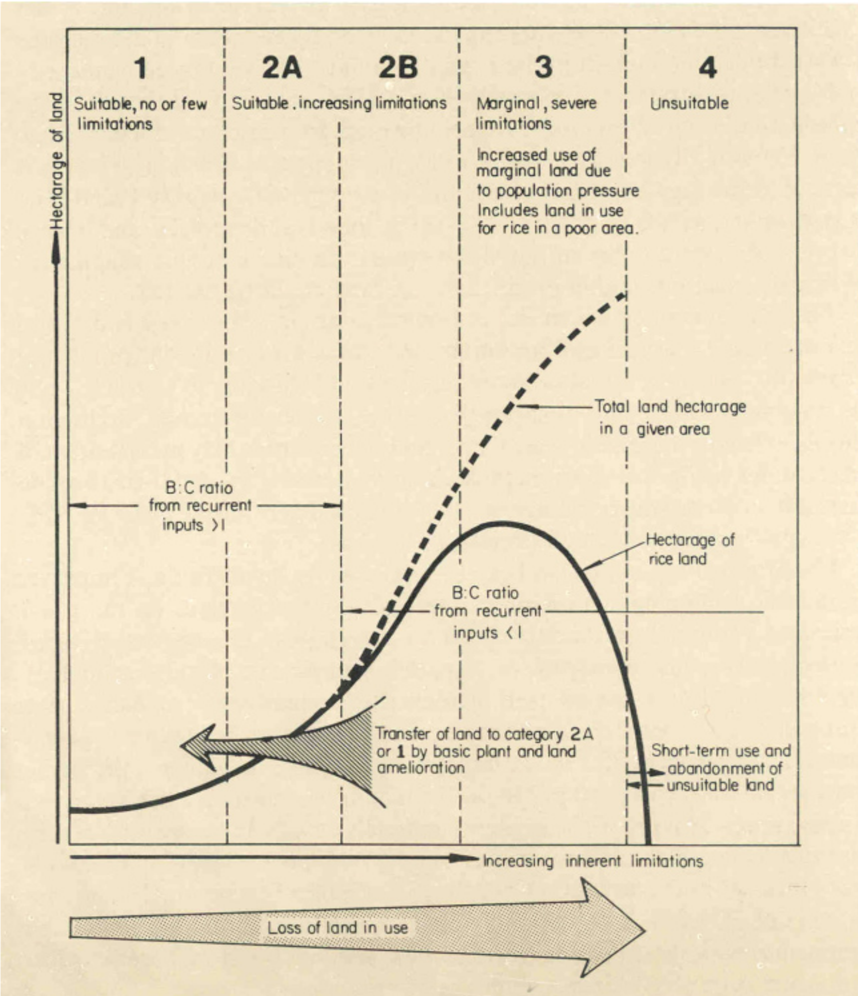
A review of the influence of climate-related land qualities is found in *Climate and rice* (IRRI, 1976).

LAND UTILIZATION FOR RICE GROWING

In the previous section we discussed land qualities as they influence the performance and ultimately the yield of the rice crops. Yield can be seen as the resultant of the many land qualities discussed.

Considering land actually used for rice growing, or potentially suited for the crop, the area of land types for which all land qualities are at or near optimum is extremely restricted. Generally, one or several land qualities are not optimal, even when such qualities as *moisture availability* and *nutrient availability* are improved by irrigation and application of fertilizers. Actual or potential rice land, therefore, can be grouped in a continuous sequence from land where environmental constraints are few and not serious to land where such constraints are so serious that rice will only yield marginally. Some land not suited to rice growing may be used anyway, but it is abandoned after a short period— usually one season — when it becomes clear to the farmer that returns in terms of yield do not cover costs of even the most basic inputs.

The relationship between the hectarage of the rice lands and their quality or, conversely, the increasingly serious constraints imposed by the environment is schematically represented in the model in Figure 5. Arbitrarily, rice lands may be subdivided into four categories as follows:



5. This model shows the relationship of land quantity to land use for rice growing.

- *Category 1* pertains to land of excellent inherent quality with no or only slight limitations.
- *Category 2* is land suitable for rice cultivation but with increasingly severe limitations, usually requiring increasingly costly measures for land improvement.
- *Category 3* is land that is marginally suited for rice because of its severe limitations. For such land, either continuous use for rice-based cropping systems is not possible or adverse factors such as a severe drought during the growing season regularly cause crop failure.
- *Category 4* is land that is unsuited for crops, including rice, because of environmental limitations. Because of population pressure or poor technical planning, such land may be locally cleared for rice growing, but is soon abandoned due to persistent crop failure and progressive land deterioration — acidification in high pyrite mangrove muds, erosion in steep land, etc.

Figure 5 illustrates that relatively little land of category 1 is available, either in its natural state or after improvement by man. In the rice-producing areas of Asia, virtually all category 1 land is in rice production, increasingly with a high level of technology. On other continents some potential category 1 land is not in general use as rice land. Such land can be found on flood plains and in small depressions where, after an initial investment for clearing, land shaping and eventual irrigation, highly productive rice land could be created.

The bulk of land on which rice is grown belongs in categories 2 and 3, with one or more environmental limitations causing a lower inherent production capability. Whereas actual or potential rice land belonging to category 2 may be expected to have land qualities that assure reasonable annual production, this is no longer the case for category 3 land, where crops may recurrently fail. In the older rice-growing areas, most category 2 land is in use for rice production and an increasing hectarage of category 3 land is being *put under the plow,* especially in areas with high population pressure.

The productivity of rice land can be increased by intensified and improved agronomic technology. Modern rice technology concentrates on the use of improved varieties, appropriate use of fertilizers, pest (disease, insect, weed) control, and water management. Another component of this technology, mechanization, does not by itself increase the productivity of a given surface unit of land. Nevertheless, amortization on investment relating to mechanization must be considered. For the improved agronomic technology, the farmer must spend for recurrent input in the form of improved seeds, fertilizers, pesticides, water delivery to the field, operational costs and amortization of farm machinery, etc. The returns on such purchased inputs must, of necessity, be more than the expenditure they require, i.e. the benefit: cost (B:C) ratio must exceed one. The B:C ratio is high for land with an inherent high potential, but diminishes with increasing environmental constraints, and becomes less than one when such constraints severely limit production. For instance, on land where availability of moisture is poor and restricts production, the use of fertilizers often does not pay. Hence, many farmers will not use fertilizers on such land, even if these are available.

In the model of Figure 5, the relationship between increasing natural restraints and the B:C ratio of recurrent purchased inputs has been indicated. In cagetory 1 land, the returns on such inputs are high and it is, therefore, understandable that there the impact of the new technology has been felt most. The B:C ratio may be expected to drop below one in the lower category land if the entire package of inputs is considered. Therefore, in the model, the category 2 land is arbitrarily divided into subcategory 2A, where the B:C ratio is larger than one, and subcategory 2B, where the B:C ratio is lower than one and where most or all purchases of such inputs are unprofitable. The B:C ratio must be considerably higher than one before small farmers venture into use of the improved rice technology. This is a main reason why, in spite of the great potentials of the modern rice varieties and their accompanying technology, considerably less than the projected rice area in South and Southeast Asia is planted to them.

Of course, the B:C line varies depending on the type and cost of the recurrent inputs and on the value of the produce — the market price of the rice. Relatively cheap fertilizers, eventually subsidized, will tend to displace the B:C line to the right resulting in an increased hectarage of category 2A land on which fertilizers can be profitably used. Increases in fertilizer prices with unchanged rice price will diminish the hectarage of land where such inputs can profitably be used. That is exactly what has taken place in recent years due to the increased price of fossil-fuel energy.

While the effect of the B:C ratio on the use of purchased inputs is, therefore. variable in time, it also varies among countries and even among regions within a country. Generally speaking, prices for purchased inputs are relatively lower in the more developed nations where such inputs as agricultural chemicals are locally produced. At the same time the returns to the farmer for his produce are sufficiently high due to better market organization and, often, to price control so that high-technology rice cultivation becomes profitable. This is not normally the case in the developing countries of the tropics and subtropics, especially in those with a surplus of rice and with low remuneration to the farmers for their produce.

The consequences of these basic economic considerations are important. When evaluating land for its potential with modern rice technology, at least a basic understanding of the economic aspects is essential. If environmental restraints are severe, such improved technology may not, and often does not, pay.

Judicious application of recurrent inputs, combined with improved agricultural technology, will increase the productivity of land with little capital investment where such inputs are economically viable. Another approach to the problem of increased production is the transfer of land from a lower to a higher category, so that recurrent inputs would be economic. In terms of the model this can be achieved by diminishing or eliminating the effect of one or more of the production-limiting constraints that determine the present production ceiling of the land.

Two major ways to reach such an objective are available, as indicated in the model. Basic land amelioration is the first and most obvious one and is applied globally, not only for rice but for agriculture in general. By introducing irrigation, land that would normally have low available moisture for the rice crop is transformed to category 1 land if lack of moisture was the only, or at least the major, restraint. Similar improvement of land qualities can be expected from protection against floods, from drainage of poorly drained soils, etc. Bear in mind that in such projects, the recurrent costs will increase if the capital inputs required for basic land amelioration must be amortized.

Extensive development projects may fail where the sharply increased recurrent costs are not covered by the improved productivity of the land, mainly because environmental restraints remain severe. Thus. many reclamation projects in potentially acid mangrove lands have failed because while certain land qualities were improved, the negative land quality caused by acidification remained or became more serious after empoldering and æration of the soil.

The second approach to the transfer of land to a more remunerative category is by basic plant amelioration — development of rice varieties adapted to inherent production restraints of the land. This requires breeding and screening programs for so-called problem soils. Rice breeding programs generally remain primarily oriented toward higher yields and resistance to insects and diseases, but the proposed approach would be much more location-specific. This means that rice improvement programs should be oriented toward overcoming or negating environmental constraints while simultaneously improving locale-specific agronomic practices. Thus, the development of modern varieties resistant to salinity, iron toxicity, drought, or other environmental constraints would tend to *transfer* land from its present low category 3 or 2B to a higher category 2B or even 1 for that specific new adapted variety.

Location-specific breeding and the development of agronomic practices for less than ideal environmental conditions should, of course, go hand in hand with the first approach, the basic improvement of the land.

The last element in the model is the effect of improper land use. Deterioration of land by man-induced erosion, by salinization and acidification, and by other causes is well documented and has assumed catastrophic proportions in many project areas. While deterioration of rice land is generally not so severe as for other land-use types, there are nevertheless many cases where rice land has lost part or all of its qualities. Erosion of pluvial rice lands may be more severe than that of other land-use types. Increased incidence of damaging floods in lowlands, due to deforestation and overuse of the uplands in catchment areas of rivers, has diminished productivity of rice lands in many river basins. The development of a poorly drained condition and salinization due to improper irrigation practices are all too well known in various lower river basins, especially in the more arid areas.

Applying the model of Figure 5 on a regional or national basis, the shape and distribution of land in use for rice over the various categories is not nearly the same under all conditions. In economically and technically advanced countries, a high proportion of the land in use is in categories 1 and 2A. Here, only better land is used or existing rice land has been improved to such a degree that it falls into a remunerative category. In most intertropical rice-growing countries, however, neither present quality of the land in use, nor the economic and technical parameters are anywhere near optimum. Therefore, most progress can be expected here from modern rice techniques developed by the integrated effort of breeders, agronomists, and land-oriented scientists.

References

ADRIESSE, J. P. 1974. Tropical lowland peats in South-East Asia. R. Trop. Inst. Comm. No. 63, Amsterdam. 63 p.

BERTRAND, R. 1973. Contribution ál'étude hydrologique pédologique, et agronomique des sols gris sableux hydromorphes de Casamance (Senegal). Agric. Trop. 27(12):1145–1192.

BRAMMER, H. 1971a. Soil survey project, Bangladesh: agricultural development possibilities. Tech. Rep. 2, FAO, Rome. 153 p.

BRAMMER, H. 1971b. Soil survey project, Bangladesh: Soil Resources. Tech. Rep. 3, FAO, Rome. 211 p.

BRAMMER, H., and R. BRINKMAN. 1977. Surface-water Gley Soils in Bangladesh. Environment, landforms, and soil morphology. Geoderma 17:91–109.

BRINKMAN, R., and L. J. PONS. 1968. A pedomorphological classification and map of the Holocene sediments in the coastal plain of the three Guianas. Soil Survey Paper 4, Wageningen. 44 p.

BRINKMAN, R. 1970. Ferrolysis, a hydromorphic soil forming process. Geoderma 3(3);199–206.

BRINKMAN, R. 1977. Surface-water Gley soils in Bangladesh. Genesis. Geoderma 17:111-144.

BROADBENT, F. E. 1978. Nitrogen transformation in flooded soils. Pages 543-560 in International Rice Research Institute. Soils and rice. Los Baños, Philippines.

BROWN, F. R. 1969. Upland rice in Latin America. Int. Rice Comm. Newsl. 18:l–15.

BUOL, S. W., P. A. SANCHEZ, R. B. CATE, JR., and M.A. GRANGER 1975. Soil fertility capability classification: a technical soil classification for fertility management. Pages 126–141 *in* Soil management in tropical America. North Carolina State University, Raleigh.

CASTRO, R. V. [U.], and S. R. SABADO. 1977. Influence of varying level of salt applied at different stages on the growth and yield of rice. Grains J. 2(3):43-45.

CASTRO, R. U. 1977. Zinc deficiency in rice: a review of research at the International Rice Research Institute. Int. Rice. Res. Inst. Res. Pap. Ser. So. 9. 18 p.

CENTRAL SOIL SALINITY RESEARCH INSTITUTE (CSSRI). 1974. Annual report, Karnal, India. 95 p.

CHANG, T. T. 1976. The origin, evolution, cultivation, dissemination, and diversification of Asian and African rices. Euphytica 25(2):425–441.

CHEN, T. T., K. H. HOUNG, and C. T. WEI. 1969. Water management of a paddy as related to physico-chemical properties of the soil. Soils Fert. Taiwan 16:30–45.

COCHEME, J. 1971. Notes on the ecology of rice in West Africa. Pages 1-6 *in* Notes on the ecology of rice and soil suitability for rice cultivation. AGS/WARDA/71/5. FAO, Rome.

CONKLIN, H. C. 1957. Hanunoo agriculture: a report on an integral system of shifting cultivation in the Philippines. Food and Agricultural Organization of the United Nations. Rome. 299 p.

COMMISSION DE PEDOLOGIE ET DE CARTOGRAPHIE DES SOLS, 1967. Classification des sols. Lab. Geol. Pedol., Ecol. Nat. Super. Agron. Grignon, France. 87 p.

CURFS, H. P. F. 1976. Systems development in agricultural mechanisation with special reference to soil tillage and weed control. Communications Agricultural University, Wageningen. The Netherlands 76–5. 179 p.

DE DATTA, S. K., and H. M. BEACHELL. 1972. Varietal response to some factors affecting production of upland rice. Pages 685–700 in International Rice Research Institute. Rice breeding. Los Baños, Philippines.

DE DATTA, S. K. 1975. Upland rice around the world. Pages 2–11 *in* International Rice Research Institute. Major research in upland rice. Los Baños, Philippines.

DE DATTA, S K., K. A. GOMEZ, R. W. HERDT, and R. BARKER. 1976. Farm yield constraints Laguna, Nueva Ecija. Camarines Sur, and Iloilo province sites, Philippines. 1975. Paper No. 5, Int. Rice Agro-Econ. Network Workshop, International Rice Research Institute, Los Baños. Philippines. 49 p.

DEI, T., and K. MAEDA. 1973. On soil structure of plowed layer of paddy field. JARQ (Jpn. Agric. Res. Q.) 7:86–92.

DE RIDDER, N. A. 1975. Hydrogeological investigations in Haryana State. India. International Institute Land Reclamation and Improvement. Annual Report for 1975. Wageningen.

DUDAL, R. 1958. Paddy soils. Int. Rice. Comm. Newsl. 7(2):19–27.

DUDAL, R. 1963. Dark clay soils of tropical and subtropical regions. Soil Sci. 95:264-270.

DUDAL, R., and F. R. MOORMANN. 1964. Major soils it Southeast Asia. J. Trop. Geogr. 18:54–80.

EZAKI, K. 1975. Drainage of paddy field in Japan. Symposium water management in rice field. Tropical Agricultural Research Center. Ministry of Agriculture and Forestry, Japan. Tech. Rep. 16. 18 p.

FERGUSON, J.A.,J.T. GILMOUR, and C.L. GRIFFIS. 1973, Distribution pattern of Ca and Mg precipitates in flooded ricefields. Arkansas Farm Rev. 22(6):2.

FLACH, K. W., and D. F. SLUSHER. 1978. Soils used for rice culture in the United Stares. Pages 199-214 *in* International Rice Research Institute. Soils and rice. Los Baños, Philippines.

FOOD and AGRICULTURE ORGANIZATION of the UNITED NATIONS. 1976. Soils Bull. 32. A framework for land evaluation. Rome. 72 p.

FUKUI, H. 1971. Environmental determinants affecting the potential dissemination of high yielding varieties of rice. Southeast Asian Stud. 9:348–374.

GRANT, C. T. 1965. Soil characteristics associated with wet cultivation of rice. Pages 15–28 in International Rice Research Institute. The mineral nutrition of the rice plant. Johns Hopkins Press, Baltimore, Maryland.

HARADA, T., H. HASHIMOTO, and M. HARA. 1955. Studies on the organo-mineral colloidal complexes of paddy soil. Part 2. Humus contained in the GI of degraded paddy soils. Soil Plant Food 1: 105–108.

HAUSER, G. F., and R. SADIKIN. 1956. The productivity of the soils of East Central Java, based on the yields of Jawa rice. Gen. Agric. Res. Stn., Bogor No. 144. 98 p.

HIGGINS, G. M. 1964. Soils of some rice growing areas in north Nigeria. Afr. Soils 9(2):217–265.

HUIZING, H. G. J. 1971. A reconnaissance study of the mineralogy of sand fractions from East Pakistan, sediments and soils. Geoderma 6:109–133.

HUKE, R. E. 1976. Geography and climate of rice. Pages 31–50 *in* International Rice Research Institute. Climate and rice. Los Baños, Philippines.

KEHASHI, H., and F. N. PONNAMPERUMA 1978. Varietal tolerance of rice to adverse soils. Pages 801-823 *in* International Rice Research Institute. Soils and rice. LOS Baños, Philippines.

ILACO-NEDECO. 1966. Report on the soil investigation in the Niger Delta special area. Niger Delta Development Board, Port Marcourt. 161 p.

INTERNATIONAL RICE RESEARCH INSTITUTE (IRRI). 1972. Annual report for 1971, Los Baños, Philippines. 238 p.

INTERNATIONAL RICE RESEARCH INSTITUTE (IRRI). 1975. Annual report for 1974. Los Baños, Philippines. 479 p.

INTERNATIONAL RICE RESEARCH INSTITUTE (IRRI). 1976. Annual report for 1975. Los Baños, Philippines. 418 p.

INTERNATIONAL RICE RESEARCH INSTITUTE (IRRI). 1976. Climate and rice. Los Baños, Philippines. 565 p.

INTERNATIONAL RICE RESEARCH INSTITUTE (IRRI). 1978. Annual report for 1977. Los Baños, Philippines. 548 p.

INTERNATIONAL RICE RESEARCH INSTITUTE (IRRI). 1978. Soils and rice. Los Baños, Philippines. 825 p.

INTERNATIONAL RICE RESEARCH INSTITUTE (IRRI). 1984. Terminology for rice growing environments. Los Baños, Philippines. 35 p.

JANITZKY, P., and L. D. WHITTIG. 1964. Mechanisms of formation of Na_2CO_3 in soils. II. Laboratory study of biogenesis. J. Soil Sci. 15:145–157.

KAMPEN, J. 1970. Water losses and water balance studies in lowland rice irrigation. Ph.D. thesis. Cornell University.

KANAPATHY, K. 1975. Growing crops on peat soils. Soils and Analytical services Bull. 4. University of Agricultural Rural Development of Malaysia. 64 p.

KANG SEK HJON, and S. MARKERT. 1959. Ein Beitrag zur Kenntnis nordostkoreanisher Reisboden. I. Albrecht Thaer Arch. 4:262–292.

KANNO, I. 1956. A scheme for soil classification of paddy fields with special reference to mineral soils. Bull. Kyushu Agric. Exp. Stn. 4:261–273.

KANNO, I. 1962. A new classification system for rice soils in Japan. Pedologist 6:2–10.

KANNO, I., Y. HONYO, S. ARIMURA, and S. TOKUDOME. 1964. Genesis and characteristics of rice soils developed on polder lands of Shiroishi area, Kyushu. Soil Sci. Plant Nutr. 10:l-20.

KARMAKOV, I. I. 1966. Alteration of tropical soils under cultivation. Sov. Soil Sci. 1:31–43.

KATO, T. 1972. On the water soluble organic matter in paddy soils (Part 1). J. Sci. Soil Manure, Jpn. 43:357-396.

KAMAGUCHI, K., and Y. MATSUO. 1957. Re-investigation on distribution of active and inactive oxides along soil profiles in time series of dry rice fields in polder lands of Kojima Basin. Soil Plant Food 3:29–34.

KAWAGUCHI, K., and K. KYUMA. 1969a. Lowland rice soils in Malaysia. Reports on research in Southeast Asia. Natl. Sci. Ser. No. 5, Kyoto. 154 p.

KAWAGUCHI, K., and K. KYUMA. 1969b. Lowland rice soils in Thailand. Reports on research in Southeast Asia. Natl. Sci. Ser. No. 4. Kyoto. 270 p.

KAWAGUCHI, K., and K. KYUMA. 1974a. Paddy soils in tropical Asia. 1. Description of fertility characteristics. Southeast Asian Stud. 12(1):3–24.

KAWAGUCHI, K., and K. KYUMA. 1974b. Paddy soils in tropical Asia. 2. Description of material characteristics. Southeast Asian Stud. 12(2):177-192.

KAWAGUCHI, K., and K. KYUMA. 1977. Paddy soils in tropical Asia. Their material nature and fertility. The University Press of Hawaii, Honolulu. 258 p.

KOENIGS. F. F. T. 1950. A "sawah" profile near Bogor (Java). Trans. IV Int. Congr. Soil Sci. 1:297–300.

KOSTENOV, H. 1975. Genetic and chemical characteristics of Meadow Gley Soils in the ricefields of Primoýre. Pochvovedeniya (6):23–31.

KYUMA, K., and K. KAWAGUCHI. 1966. Major soils of Southeast Asia and the classification of soils under rice cultivation. Southeast Asian Stud. 4:290–312.

LE BUANEC, B. 1975. La riziculture pluviale en terrain drainé. Situation, problémes et perspectives. Agric. Trop. 30(4):358-381.

LEUNG, K. W., and C. Y. LAI. 1973. The characteristics and genesis of paddy soils in northern part of Taiwan. Agric. Res. 22:77–97.

LYNN, W. C., and L. D. WHITTIG. 1966. Alteration and formation of clay minerals during cat clay development. Pages 241–248 *in* Proc. 14th National Conference on Clays and Clay Mineral.

MATSUO, H., A. J. PECROT, and J. RIQUIER. 1978. Rice soils of Europe. Pages 193-198 *in* International Rice Research Institute. Soils and rice. Los Baños. Philippines.

MATSUZAKA, Y. 1969. Study on the classification of paddy soils in Japan [in Japanese, English summary]. Bull. Natl. Inst. Agric. Sci. Ser. B, 20:155–349.

MITSUCHI, M. 1960. Profile differentiation of surface water type paddy soils under different drainage conditions [in Japanese]. J. Sci. Soil Manure, Jpn. 39:233–276.

MITSUCHI, M. 1974a. Pedogenic characteristics of paddy soils and their significance in soil classification. Bull. Natl. Inst. Agric. Sci. B, 25:29–112.

MITSUCHI, M. 1974b. Chloritization in lowland paddy soils. Soil Sci. Plant Nutr. 20:108–116.

MITSUCHI, M. 1975. Permeability series of lowland paddy soils in Japan. JARQ (Jpn. Agric. Res. Q.) 9:20–23.

MOORMANN, F. R. 1961. The soils of the Republic of Vietnam. Ministry of Agriculture, Saigon. 66 p.

MOORMANN, F. R., and R. DUDAL. 1968. Characteristics of soils on which paddy is grown in relation to their capability classification. 11th session IRC, Kandy, Paper S/68/7b. 14 p.

MOORMANN, F. R., and L. J. PONS. 1974. Characteristics of mangrove soils in relation to their agricultural land use and potential. Pages 529–537 *in* Proceedings of the international symposium on biology and management of mangroves. Honolulu, Hawaii.

MOORMANN, F. R., W. J. VELDKAMP and J. C. BALLAUX. 1977. The growth of rice on a toposequence — a methodology. Plant Soils. 48 p.

MOORMANN, F. R., and B. T. KANG, 1978. Microvariability of soils in the tropics and its agronomic implications with special reference to West Africa. Pages 29-43 *in* Diversity of Soils in the Tropics. ASA-SSSA Spec. Publ. 34.

MOTOMURA, S. 1969. Dynamic behavior of ferrous iron in paddy soils. (JARQ) Jpn. Agric. Res. Q. 4:12–17.

MOTOMURA, S., F. M. LAPID and H. YOKOI. 1970. Soil structure development in Asiatic polder soil in relation to iron forms. Soil Sci. Plant Nutr. 16:47–54.

MURTHY, R. S. 1978. Rice soils of India. Pages 3–17 *in* International Rice Research Institute. Soils and rice. Los Baños, Philippines.

NAGARAJA, V. N. 1964. Hydrometeorological and tidal problems of the deltaic areas in India. Pages 115–121 *in* Proc. of the UNESCO symposium on scientific problems of the humid tropical zone deltas, Dacca.

NAKAGAWA, S. 1975. Water requirements and their determination. *In* Symposium on water management in rice fields. Tropical Agricultural Research Center, Technical Report. (mimeo.)

PANABOKKE, C. R. 1978. Rice soils of Sri Lanka. Pays 19—33 *in* International Rice Research Institute. Soils and rice. Los Banos, Philippines.

PEARSON G. A., and A. D. AYRES. 1960. Rice as a crop for salt affected soils in process of reclamation. USDA Prod. Res. Rep. 43. 13 p.

PHILLINS, E. 1963. Profiles and permeability in Malayan padi soils. Malay. Agric. J. 44:3–17.

POLAK, B. 1952. Veen en veenontginning in Indonesia. M.I.A.I. 5 and 6, Vorrink, Bandung, Indonesia.

PONNAMPERUMA, F. N. 1972. The chemistry of submerged soils. Adv. Agron. 24:29–88.

PONNAMPERUMA, F. N., T. ATTANAKADA, and G. BEYE. 1973. Amelioration of three acid sulfate soils for lowland rice. Pages 391–406 *in* Proc. Acid Sulfate Soils Symp. ILRI Publ. 18 Vol. 11. Wageningen.

PONNAMPERUMA, F. N. 1976. Specific soil chemical characteristics for rice production in Asia. Int. Rice. Res. Inst. Res. Pap. Ser. No. 2. 18 p.

PONS, L. J. 1973. Outline of the genesis, characteristics, classification, and improvement of acid sulfate soils. Pages 3–27*in* Proc. Acid Sulfate Soils Symp. ILRI Publ. 18 Vol. I. Wageningen.

RAYMUNDO, M.E., E.B. PANTASTICO, and V.T. MANASPAC. 1962. Some physical and chemical properties of an upland soil and its associated paddy soils. Philipp. Agric. 46:560–569.

REDDY, K. R., and W. H. PATRICK. 1975. Effect of alternate aerobic and anaerobic conditions on redox potential, organic matter decomposition, and nitrogen loss in a flooded soil. Soil Biol. Biochem. 7:87–94.

RICE, O.W. 1969. Notes on soil temperature regimes in Thailand. Land Dev. Dep., Soil. Surv. Rep. No. 79. Bangkok. 26 p.

SANCHEZ, P. A. 1976. Properties and management of soils in the tropics. John Wiley and Sons, New York. 618 p.

SCHELTEMA, W. 1974. Puddling against dry plowing for lowland rice culture in Surinam. Agric. Res. Rep. 828, Pudoc, Wageningen. 241 p.

SHIGA, H., and W. VENTURA. 1976. Nitrogen supplying ability of paddy soils under field conditions in the Philippines. Soil Sci. Plant Nutr. 22:307–399.

SINANUWONG, S., and Y. TAKAYA. 1974a. Saline soils in northeast Thailand. Southeast Asian Stud. 12(1): 105–120.

SINANUWONG, S., and Y. TAKAYA. 1974b. Distribution of saline soils in Khorat basin of Thailand. Southeast Asian Stud. 12(3):365–382.

SOEPRAPTOHARDJO, M., and P. M. DRIESSEN. 1976. The lowland peats of Indonesia. A challenge for the future. Soil. Res. Inst. Bogor 3:11–19.

SOO SWEE WENG. 1975. Semi-detailed soil survey of the Kelantan plain. Soil Surv. Rep. No. 2. Minist. Agric. Nat. Res., Kuala Lumpur. 58 p.

TABBAL, D. F., and T. H. WICKHAM. 1976. The effects of location and water supply on water shortages in an irrigated area. Paper presented at a Saturday seminar, 26 June 1976. International Rice Research Institute, Los Baños, Philippines. 8 p. (mimeo.)

TAKAYA, Y. 1971. Physiography of rice lands in the Chao Phraya Basin. Southeast Asian Stud. 9:375–397.

TAKIJIMA; Y. 1963. Studies on the behaviour of the growth inhibiting substances in paddy soils with special reference to the occurrence of root damage in the peaty paddy field [in Japanese]. Bull. Natl. Inst. Agric. Sci. Ser. B, 13:117–397.

TANAKA, A. 1978. Role of organic matter. Pages 605–622 *in* International Rice Research Institute. Soils and rice. Los Baños, Philippines.

TANAKA, A., and S. YOSHIDA. 1970. Nutritional disorders of the rice plant in Asia. Int Rice Res. Inst. Tech. Bull. 10. 51 p.

UNESCO (UNITED NATIONS EDUCATIONAL, SCIENTIFIC and CULTURAL ORGANIZATION). 1974. FAO-Unesco Soil map of the world 1:5,000,000 Vol. 1. Legend. Paris.

USDA (UNITED STATES DEPARTMENT of AGRICULTURE), SOIL CONSERVATION SERVICE. 1960. Soil classification. A comprehensive system. U.S. Government Printing Office, Washington, D.C. 260 p.

USDA (UNITED STATES DEPARTMENT of AGRICULTURE), SOIL CONSERVATION SERVICE, SOIL SURVEY STAFF. 1975. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. USDA Agric. Handb. 336. U. S. Government Printing Office, Washington, D.C. 754 p.

VAN BREEMEN, N., L.R. OLDEMAN, and W. G. WIELEMAKER. 1970. The Ifugao rice terraces. Pages 39–74 *in* Aspects of rice growing in Asia and The Americas. Misc. Pap. 7. Landbouwhogeschool, Wageningen.

VAN BREEMEN, N. 1973. Dissolved aluminum in acid sulfate soils and in acid mine waters. Proc. Soil. Sci. Soc. Am. 37(5):694–697.

van Breemen, N. 1975. Acidification and deacidification of coastal plain soils as a result of periodic flooding. Proc. Soil Sci. Soc. Am. 39:1153–1157.

van Breemen, N. 1976. Genesis and solution chemistry of acid sulfate soils in Thailand. Center for Agricultural Publishing and Documentation. Wageningen. 263 p.

Van der Kevie, W., and B. Yenmanas. 1972. Detailed reconnaisance survey of the Southern Central Plain Area. Soil Survey Report 89. Soil Survey Division, Bangkok, 187 p.

Van Wambeke, A. 1975. Management properties of oxisols in Savannah eco-systems. Pages 364–371 *in* Soil management in tropical America. Raleigh, North Carolina.

Wada, H., and S. Matsumoto. 1973. Pedogenetic process in paddy soils. Pedologist 17:2–15.

Wada, H., M. Okazaki, and Y. Takai. 1975. Dissolution of ferri hydroxide with the leachate from the waterlogged soil. I. Role of water soluble substances in dynamics of paddy soil. J. Sci. Soil Manure. Jpn. 46:201–244.

WARDA (West African Rice Development Association). 1975. Rice vocabulary. Monrovia. 207 p.

Westfall, D. G. 1975. Rice soils, properties, and characteristics. Pages 22–30 *in* Six decades of rice research in Texas. Texas Agric. Exp. Stn.

Whistler, F. D., J. C. Lance, and R. S. Linebarger. 1974. Redox potentials in soil columns intermittently flooded with sewage water. J. Environ. Qual. 3:60–74.

Wickham, T. H. 1973. Predicting yield benefits in lowland rice through a water balance model. Pages 155–181 *in* International Rice Research Institute. Water management in Philippine irrigation systems: research & operations. Los Baños. Philippines.

Wijewardene, R. 1975. Engineering's research at MARDI for Malaysia's farming future. Agric. Mech. Asia 6(1):20–24.

Wole. J. N. 1975. Soil-water relationships in oxisols from Puerto Rico and Brazil. Pages 145-154 *in* Soil management in tropical America. Raleigh, Sorth Carolina.

Yanagisawa, M., and J. Takahasi. 1964. Studies on the factors related to the productivity of paddy soils in Japan with special reference to the nutrition of the rice plants. Bull. Natl. Inst. Agric. Sci. Jpn. Scr. B, 14:41–171.

Yong Hwa Shin. 1978. Rice soils of Korea. Pages 179–191 *in* International Rice Research Institute. Soils and rice. Los Baños, Philippines.

Yoshino. T., and Y. Die. 1977. Prediction of nitrogen release in paddy soils by means of the concept of effective temperature. Cent. Afr. Exp. Stn. (Konosu Saitama, Japan) 25:l–62.

Glossary

This glossary contains terms from certain specialist areas, terms newly proposed in this book, and some more or less generally used terms that need a more precise definition for use in this book. An italicized word signifies that its definition is included in the glossary. Definitions from *Soil taxonomy* (USDA, 1975) are abbreviated. For a more complete terminology and for definitions of taxa mentioned in this book, we refer the reader to *Soil taxonomy.*

albic horizon — a soil horizon from which clay and iron oxide have been removed (USDA, 1975).

alluvial — pertaining to alluvium; a clayey, silty, sandy, or gravelly material deposited by a stream or other bodies of running water.

alluvial fan — cone-shaped landform of alluvial deposits created by a stream as it flows from mountain to lowland.

anthraquic — pertaining to an *aquic* soil moisture regime induced by human action such as bunding and leveling of land, or irrigation.

aquatic — pertaining to organisms living entirely or primarily in water.

aquic — pertaining to a soil moisture regime characterized by water saturation of the soil at all depths for at least a few weeks every year (USDA, 1975).

aquorizem — soil characterized by a distinct accumulation horizon of iron oxide and manganese oxide below the *traffic pan,* formed as a result of *wetland* rice cultivation (Kyuma and Kawaguchi, 1966).

argillic horizon — a soil horizon enriched by clay that has moved downward (USDA, 1975).

aridic — pertaining to a soil moisture regime typical of arid climates (USDA, 1975).

artesian water — groundwater confined under hydrostatic pressure.

backswamp — a depressed area on a river floodplain, where surface drainage is hampered by surrounding higher land.

cambic horizon — a subsurface soil horizon that has undergone marked alteration due to the soil-forming processes (USDA, 1975).

colluvial — pertaining to colluvium, a deposit of soil and rock material at the base of a slope.

dryland — pertaining to soils rarely or never flooded, or to crops grown in such soils.

ferrolysis — a soil-forming process resulting in acidification and clay destruction due to alternating reduction and oxidation in periodically flooded soils (Brinkman, 1970).

fluxial — pertaining to flooding by surface water conveyed from elsewhere.

gley — pertaining to grayish, greenish, and bluish soil colors resulting from waterlogging and reduction of the soil material.

hydromorphic — pertaining to a soil showing characteristics associated with permanent or periodic excess water, e.g. *gley* phenomena.

interflow — shallow and often ephemeral and perched groundwater moving laterally.

lacustrine — pertaining to lakes.

mangrove — tropical or subtropical vegetation (mainly trees) typical of tidal swamps.

meander — one of a series of approximately sinuous curves or windings in the course of a river or creek.

mollic epipedon — thick, dark surface soil horizon, highly saturated with bivalent cations (Ca^{++} and Mg^{++}) (USDA, 1975).

paddy — 1. *Wetland* rice. 2. Bunded and leveled field used for cultivation of rice. The original meaning of paddy (Malay *padis)* is threshed, unhulled rice.

peneplain — land surface worn down by erosion to a nearly flat or broadly undulating plain.

perudic — pertaining to a soil moisture regime where rainfall exceeds evapotranspiration throughout the year and where the soil never dries completely (USDA, 1975).

phreatic — pertaining to groundwater. Used in this book to indicate groundwater that periodically rises to the rooting zone of cultivated plants.

piedmont plain — a broad slope composed of alluvial or colluvial sediments, or both, extending along and from the base of a mountain range.

piezometer — an open-ended tube placed vertically in the soil for measurement of the hydrostatic pressure level of groundwater.

pluvial — pertaining to rain; also pertaining to land that receives water almost wholly directly from rain.

puddling — tillage of water-saturated soil.

pyroclastic — pertaining to broken fragments of volcanic origin — ash and rock material.

taxon (pl. taxa) — unit of any rank in a classification system.

terrace *(alluvial)* — any stretch of relatively level land, bounded along one edge by a descending slope and along the other edge by an ascending slope, mostly marking a former *alluvial* sedimentation level.

toposequence — a sequence of soils in the landscape, from the crest to the valley bottom.

traffic pan — a 5- to 10-cm thick compacted subsurface horizon between the 10- and 40-cm depths; common in *paddies.*

udic — pertaining to a soil moisture regime where the soi1 is not dry for as long as 90 cumulative days (USDA, 1975).

ustic — pertaining to a soil moisture regime characterized by limited moisture during most of the year but with at least 1 rainy season of 3 months or more (e.g., in a monsoon climate) during which the soil is moist (USDA, 1975).

wetland — pertaining to soils flooded for at least several weeks each year, or to crop grown in such soils.

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