Guy D. Smith Memorial Slide Collection

Properties, Classification and Management of Oxisols

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A copy will be made available to teachers of Soil Taxonomy and specifically, soils of the tropics. Only a limited number of this monograph was produced. A copy may be obtained by writing to:

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FOREWORD

Oxisols occupy about 23 percent of the land surface of the tropics and are the single most extensive kind of soil in that region. Oxisols thus constitute a major land resource and they also represent one of the few remaining frontiers for agricultural development. As the human-induced pressure on the Earth's land resources grows, so does the importance of Oxisols for food production. Yet, although the knowledge of tropical soils in general and Oxisols in particular has increased substantially in the past decades and scientific fact has gradually replaced myths, there still prevail misconceptions and erroneous notions about the nature, properties and production potential of these soils.

The growing interest in Oxisols has led to the greater emphasis on these soils in soil science curricula. However, not many people have had the opportunity to travel extensively in the tropics and study and photograph these soils *in situ*. ***The intent and purpose of the slide set therefore is to provide teachers and students of pedology with basic information and illustrations about the formation, classification, properties, management, and environmental aspects of Oxisols.***

The text information presented is a distillation of essential characteristics of Oxisols and as such is not exhaustive and cannot substitute for the in-depth study of these soils. Rather, the principal purpose of the slide set is to provide teachers with access to quality visual aids which otherwise would not be available to them.

To enhance flexibility of use, the slide set has been structured into nine independent modules. Each of these may be used individually or in any combination with other modules of the set. The topics of the modules are:

Module I	Historical Background
Module II	Concept, Definition and Diagnostic Criteria
Module III	Taxonomic Classification
Module IV	Formation and Landscape Relationships
Module V	Morphology
Module VI	Properties
Module VII	Global Extent and Geographic Distribution
Module VIII	Use and Management
Module IX	Sustainable Development Considerations.

The text which accompanies the slides provides a brief narrative for each of the sequentially numbered slides of the set. These statements are intended to guide the users and complement their knowledge, if necessary. The narratives for the slides are presented in text boxes. Further pertinent information of a more general nature and therefore not keyed to a specific slide is inserted between the boxes and printed in italics.

Ample references are cited which may be consulted by those seeking more detailed information. Also appended to the text are site and profile descriptions for some typical Oxisol pedons and physical, chemical, and mineralogical characterization data.

In memoriam, we dedicate this slide set to Dr. Guy D. Smith who worked tirelessly towards a World Soil Classification System.

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Properties, Classification and Management of Oxisols

INTRODUCTION

The red colors and the deep weathering profiles of some soils in the tropics are distinctive and most classification systems in the world differentiate these soils from the soils of temperate regions which have good horizonation and generally do not exceed a meter in thickness. Traditionally, there has also been a tendency to view the soils of the tropics differently from the colder temperate region soils. The vegetation and land use were additional reasons for making this distinction.

In the early literature, the highly weathered soils of the tropics were grouped under red soils, red loams, or red earths. With the description of laterites by Buchanan (Buchanan, 1807), the term laterite and lateritic soils become prevalent in the soils literature. With more studies, other adjectives were added to the term lateritic soils. In 1949, a group of scientists created the term "Latosols" (Cline, 1975) that soon became very popular despite the fact that it was not defined in rigid terms. In the soil survey of Hawaii, the terms Humic Latosols, Hydrol-humic Latosols, etc., were used. This was also the period when the concept of "podzolic soils" was being accepted and the Latosols were considered as a distinct group of soils. In the fifties and sixties, several classification systems came into vogue and other terms to describe these highly weathered soils of the tropics were coined.

By about the mid-fifties, the concept of Latosols as a highly weathered or low negative charge soil became firmly established and paved the way for the modern concept of Oxisols. The decade of the fifties also saw large advances in mineralogical studies and with increasing studies on soils of the tropics, the processes responsible for Latosol formation were better understood. During this period, the term "Ferralitic Soils" appeared in the French (Aubert, 1958) and Portuguese (Botelho da Costa, 1954) literature. The Belgians introduced the term "Kaolisols" (Sys et al., 1961; Tavernier and Sys, 1965). Charter (1958), working in Ghana, used the terms "Oxysols and Ochrasols."

The term Oxisol was created around 1954 during the development of Soil Taxonomy (Soil Survey Staff, 1975) and the definition was based largely on the Latosol concept. Thus the class of Oxisols included many of the present day Andisols, some Inceptisols, and some of the Alfisols and Ultisols. A more comprehensive definition of the term "Oxisols" was published in 1960 by USDA and the concept, definition, and classification were gradually modified and refined until the publication of Soil Taxonomy in 1975 (Soil Survey Staff, 1975). However, Dr. Guy D. Smith, the principal contributor to Soil Taxonomy, felt that the knowledge and thus the classification of soils of the tropics was incomplete and indicated that these taxa will be considerably modified. In 1978, an International Committee on Oxisols (ICOMOX) was formed (Buol and Eswaran, 1988) to initiate discussions that would lead to an improved classification. Continued development of Soil Taxonomy *lead to refinement of the definition and the most recent Keys to Soil Taxonomy (Soil Survey Staff, 1994) provides the current concept and definition.*

MODULES

MODULE I

2. Historical Background

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3. 1807 is frequently used as the benchmark year for studies on the soils of the tropics. In that year, Francis Buchanan, a British medical doctor and naturalist published his historical document of his travels in South India (Buchanan, 1807) wherein he described the material used for constructions. He coined the term "laterite" which is still used today but with a wide variety of meanings. The slide shows a monument built by the Geological Survey of India in December 1979, to commemorate Buchanan's contribution (the lower part of the monument is draped in the kilt of the Buchanan clan). The monument is built at the Government Guest House at Angadipuram, Kerala State, where Buchanan described laterite and which is today considered as the type locality. In modern terminology, the material is called plinthite and when it is exposed, it hardens to a rock-like material very suitable for construction of small structures.

The current concept and definition of Oxisols is due to the work of the International Committee on Oxisols — ICOMOX — (Buol and Eswaran, 1988). More than 100 persons from around the world contributed to the work of this committee and four international soil classification workshops — Brazil (1976), Malaysia and Thailand (1978), Rwanda (1981), and Brazil (1986) — were organized by Dr. Fred Beinroth of the University of Puerto Rico with funding from the US Agency for International Development. Proceedings of the workshops are listed in the reference section.

The persons who contributed to improving Soil Taxonomy *are too many to be listed here. Some of the more prominent scientists involved in this task of not only improving the classification of Oxisols but also soils of the tropics in general are portrayed in this module. Many of these persons were also instrumental in the development of* Soil Taxonomy *itself.*

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4. Dr. Guy D. Smith (smoking a cigar) is considered the father of *Soil Taxonomy*. In 1950, Dr. Charles Kellogg, then the Administrator of the Soil Conservation Service, charged Dr. Smith to develop a new classification system as the existing system of Thorp and Smith (1949) was proving inadequate to meet the needs of the expanding national soil survey program. Dr. Smith made this his life's challenge and guided the development of *Soil Taxonomy* not only to the time of its publication in 1975 but also almost until his death in 1983. The person in the red hat is Dr. Stanley Buol, who headed the International Committee on Oxisols (ICOMOX). The person in the blue pullover is Dr. Juan Comerma from Venezuela, who provided a South American perspective to the knowledge of Oxisols.

5. Major contributions to the classification of Oxisols were provided by the Brazilians under the leadership of Dr. Marcelo Camargo✣, with the blue cap, of EMBRAPA-SNLCS and Dr. Jacob Bennema✣ (then working for FAO). In fact, many of the basic concepts and definitions of Oxisols were modified from the Brazilian classification. In the slide are Dr. Camargo and the current Director of EMBRAPA-CNPS, Dr. Antonio Ramalho. They and their colleagues made their knowledge, experience, and database available to ICOMOX.

6. In 1978, USDA-SCS established the International Committee on Classification of Low Activity Clay soils (ICOMLAC) with Dr. Frank Moormann (then at the International Institute of Tropical Agriculture, Nigeria) as the Chairman (Moormann, 1985). Later, ICOMLAC and ICOMOX, worked together. In the slide are Drs. Moormann (white hat), Hari Eswaran (yellow hat) and Rene Tavernier✣ (red hat). Dr. Tavernier of the University of Ghent, Belgium, worked closely with Dr. Guy Smith and contributed to the terminology of Soil Taxonomy. His experience of the soils of Zaire was valuable to bring the Central African experience to the classification.

7. Oxisols have a unique mineralogy and chemistry. Dr. Goro Uehara from the University of Hawaii and his students and colleagues, provided much of the basic information to understand the properties and behavior of the colloid composition. Dr. Uehara, with the blue shirt, also provided the basic concept and definition of low activity clays.

8. European colleagues have a long history of soil survey and research in the tropics and many of the European classification systems have classes equivalent to Oxisols. Prof. Karel Sys of Belgium (whose face appears on the left of the slide), Prof. Tavernier (blue vest), Dr. Klaus Flach of USDA-SCS, Prof. Dr. Ernst Schlichting✣ of Germany, and Dr. Marcel Jamagne of France, are some of the contributors.

9. Dr. Lek Moncharoen (Thailand, with spear) and Dr. Fred Beinroth (University of Puerto Rico) jointly organized the workshop held in Thailand and Malaysia. Dr. Beinroth organized a total of 10 workshops on soil classification during the period 1976 to 1990. These workshops provided the venue for soil scientists from all over the world to meet and discuss *Soil Taxonomy*. The Circular Letters of the International Committees provided the communication among all interested persons.

10. Prof. George Aubert (ORSTOM, France) is the author of the French CPCSS classification (Aubert, 1958) and his more than 30 years of experience in the tropics provided the field information for all international classification systems. He and his school also injected the strong genetic bias in not only the French system but in all other classification systems.

11. Dr. Francesco Palmieri of Brazil is one of the soil scientists with a strong field background in soil survey who provided practical inputs to the system.

12. The slide shows the participants of the 8th. International Soil Classification Workshop held in Brazil in 1986. A major purpose of the workshop was the discussion of the issues that were highlighted in the Circular Letters of ICOMOX. State-of-the-art papers were also submitted at such workshops and were included in the proceedings. (The workshop proceedings are highlighted in the Bibliography).

MODULE II

13. Concept, Definition and Diagnostic Criteria

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14. In the fifties and sixties, several national and international soil classification systems were developed. In each, the highly weathered soils of the tropics were recognized as a unique group and the slide shows some of the names used in the other classification systems. Many of the systems did not have a rigid definition of the class and so with time, the systems faded away into the archives of soil science literature.

15, 16. During the historical development of the concept of Oxisols several myths were perpetuated. Part of the reason for this was due to the absence of reliable databases and an incomplete knowledge of the nature and properties of Oxisols. In the early years of the use of *Soil Taxonomy*, persons were not rigidly using the Keys to the classification and as a result, some soils were misclassified. This was corrected to some extent through the training courses and workshops conducted by the USDA-NRCS/World Soil Resources group.

The oxic horizon is a subsurface horizon that may appear at the surface in truncated soils. It is a diagnostic horizon created originally to define the Order of Oxisols. The key properties of the oxic horizon are the charge characteristics, and the negligible amounts of weatherable minerals. The charge characteristic is defined by the magnitude of the pH dependent charge (CEC NH_4OAc) which is less than 16 cmols^{+} kg^{-1}, and the permanent charge (estimated by the Effective Cation Exchange Capacity — ECEC) which is less than 12 cmols^{+} kg^{-1}. The low weatherable mineral requirement ensures that there is only a small amount of weatherable minerals that may alter to release plant nutrients to the soil. The low amounts of rock fragments that contain weatherable minerals is part of the definition for the same reason. The horizon has a particle size class that is sandy loam or finer which precludes coarse textured soils from having this horizon. The diagnostic horizon has also diffuse boundaries between *subhorizons indicating that soil formation has masked evidences of translocated clays. Finally, to be diagnostic, the horizon must have a minimum thickness of 30 cm.*

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17. Large contiguous areas of Oxisols are found on old geomorphic surfaces, such as the Congo Basin and the Amazon Shield. These surfaces are peneplained and are comprised of mid- to end-Tertiary deposits, some of them pre-weathered. Oxisols have developed on such deposits. In general these old peneplains are flat but some have been dissected. In SE Asia and in Oceania, where the landscapes are Quaternary, Oxisols are formed on basic or ultrabasic rocks which are highly weatherable.

18. The slide lists some of the unique properties of Oxisols.

19. Key to the identification of Oxisols is the presence or absence of two diagnostic horizons — the oxic and kandic horizon — and the particle-size class of the surface 18 cm of the soil. The slide states the definition of the **oxic horizon**. A subsurface horizon must meet all the properties to qualify for an oxic horizon.

20. The **kandic horizon** shares some of the properties of the oxic and argillic horizons. Like the argillic, it has a clay increase with depth. On the other hand, it has the charge characteristics and weatherable mineral requirements of an oxic horizon.

The Order of Oxisols is defined by not only its unique properties elaborated in the formal definition but also by its position in the Key to the Classification of Soil Orders.

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21. There are two parts to the **definition of Oxisols**. First, there should be no kandic horizon but an oxic horizon, both within 150 cm of the mineral soil surface. Second, if a kandic horizon is present, the top 18 cm has more than 40% clay and the upper boundary of the kandic horizon is within 100 cm of the mineral soil surface.

As the Oxisols are keyed out after the Histosols, Spodosols, and Andisols, Oxisols lack the properties definitive for these Orders. If not excluded by the formal definition, Oxisols may share some of the properties of the Soil Orders which are keyed out after the Oxisols.

22. There are several **categories** in *Soil Taxonomy*, with the Order being the highest category. Each of the 11 Orders has a number of Suborders each of which is divided into lower categories as shown in the slide for Oxisols. At each categorical level, *Soil Taxonomy* provides a key for the identification of the class at the next level and it is imperative that the key be used for the identification of the class. An important feature of the structure into categories is that, as the soil is placed into lower categories, the information content in the taxa name increases in two ways; first, by the definition of the category and, second, due to the elimination of the other classes (so by default the soil will not have properties definitive for the classes it does not belong to).

Diagnostic horizons, features, and properties are the defining elements to place the soil in a category. The definition and requirements are given in detail in Soil Taxonomy. *Only some of these are illustrated in this module.*

23. The **sombric horizon** is a dark colored subsurface horizon found in soils on old geomorphic surfaces of Central Africa and parts of South America. It is a distinctive horizon in the field and to some, it is indicative of a buried horizon. Its origin and genesis is still being debated but it is included as a diagnostic horizon in Soil Taxonomy due its distinctive feature in an otherwise nondescript soil. Mostly, it occurs as a continuous horizon within 1 m of the soil surface.

24. The higher organic carbon content of the **sombric horizon** is its most important property. In this low CEC soil, the higher carbon results in a higher CEC and thus the ability to store nutrients and water. In this slide from Rwanda, the sombric horizon in this road-cut is covered with moss as compared to the overlying or underlying layers. This points to some of the plant favorable properties of this subsurface horizon.

25. Some members of the Oxisols, as this soil from Brazil, have an **aquic soil water condition** whereby a major part of the soil is saturated with water during long periods of the year. When the soil is saturated, redox conditions prevail and Fe^{2+} is moved out of the system resulting in a whitish, iron impoverished soil. The iron precipitates in the lower part of the soil (not seen in the slide) and leads to the formation of plinthite.

26. **Plinthite** is a diagnostic feature of many soils which are hydromorphic or have gone through a hydromorphic phase during their evolution. The slide is a close-up of a continuous phase of plinthite in a soil from Malaysia. Plinthite is the reddish material which forms a dendritic pattern. The white material is largely kaolinite and quartz, and is devoid of iron. (Bar on left side has 10 cm intervals.)

27. In a deep profile in Kerala State, India, the lower zone is largely **plinthite** which is soft and can be cut with a knife. The upper, more reddish zone, is plinthite which is in stages of hardening towards the stage called **petroplinthite**. Hardening of plinthite takes place slowly when the ground-water table is lowered and the soil surface ground cover is removed. If the surface non-plinthic soil horizons are eroded away, the underlying plinthite is exposed and hardens rapidly to petroplinthite.

28. A **petroferric contact** is an abrupt contact between soil material and an underlying layer of hard and impermeable, cemented petroplinthite gravel. The contact is impermeable to both roots and water. The slide is of a soil (Wenchi series) in Bolgatanga, Ghana, close to the border with Burkina Faso. The petroferric contact begins at between 10 and 20 cm in this profile. During the rainy season, the soil material above the contact is saturated and there may even be ponding. Rice is grown in this condition. After the rains, a crop of millet is grown on the residual moisture stored in the top soil.

29. The surface horizon or epipedon in most lowland Oxisols is light colored and is an **ochric epipedon**. The organic carbon may be high (easily qualifying for a mollic or umbric epipedon) but the value and chroma is more than 3.5. The horizon is also usually thin, about 10 cm thick, and this is frequently lost by erosion. Residue management is a critical practice on such soils.

30. In soils of higher elevations or those with an isothermic soil temperature regime, organic matter generally increases in the surface horizon. Many of the Oxisols in cool zones have a mollic or **umbric epipedon** as shown in the slide. Presence of this epipedon is a most favorable property in these nutrient deficient Oxisols and every care must be taken to preserve these surface horizons.

MODULE III

31. TAXONOMIC CLASSIFICATION

Unlike most other classification systems, a rigid Key is used in Soil Taxonomy and it is imperative that the key is used and used properly. A first step, prior to using the key is to determine the diagnostic horizons, features and properties. Each category in the system requires a set or sets of these defining attributes. Depending on the categoric level, the attributes may be used differently, e.g., the depth at which they occur may differ or the thickness of the subhorizon portraying the property may be different. So, care must be taken when applying the Keys.

32. The **Key to the Orders** enables the placement of the soil at the Order level. If the soil does not meet the requirements of Histosols, Spodosols, or Andisols, then the soil properties are tested against the requirements for Oxisols. If the requirements are met, the Key will direct the reader to the Key for the Suborders.

33. The **Key to the Suborders** is used in the same manner as that for the Orders. This slide summarizes the requirements for Oxisol suborders. However, for correct placement, the complete definitions provided in the Key should be followed.

34. There are two important sets of **differentiating criteria** used in the classification of Suborders. The first set is the soil moisture regimes (which are discussed later) such as torric (aridic), ustic, udic, and perudic. The second is a set of criteria which together define the aquic conditions. This includes the aquic soil water conditions *ss*, the presence of a histic epipedon, and some restrictive soil color requirements. Each of these criteria adds another set of properties to the soil that is being classified.

35, 36, 37. Each of the Suborders has a set of **Great Groups**. The number of Subgroups in each Great Group is also provided in the slide. Note that the kind of Great Groups differ in each of the Suborders. For example, there is no "Sombriaquox" in the Aquox because no such soils have been described. Note that the Ustox, Udox, and Perox have the most Great Groups due to the wide extent of these soils and the large supporting database.

38. This is a summary slide showing the **formative elements** for the Great Groups and their use in each Suborder. For example, the Plinthaquox Great Group belongs to the Aquox suborder; the Eutrotorrox belongs to the Torrox suborder, and the Kandiustox great group belongs to the Ustox suborder.

39. The large number of Subgroups requires many **differentiating criteria**; some significant ones are shown in the slide.

40. Each Great Group has a number of **Subgroups** and a Key is provided for the selection of the Subgroup. In this slide, the possible Subgroups in each Great Group are presented as a matrix. Three Great Groups (Haplaquox, Sombriudox, Kandiustox) are used to illustrate the structure.

41. At the **Family** level, three differentiae are used together with the Subgroup name to name the Family class.

42. The first differentiae is the **particle-size class** and several classes are provided. Soil Taxonomy provides the definition for each class.

43. The second differentiae is the **mineralogy class** and the mineralogy classes in Oxisols are presented as a Key.

44. The third differentiae for the Family level is the **soil temperature class** and the possible soil temperature regimes are listed.

45. It is now possible to present the complete Family classification of a soil as illustrated in the slide. The **Family name** carries the Family modifiers and the name of the Subgroup. The next level is the Soil Series. The typifying Series in a Family can be used to provide an alternative and local name of the Family. For example, if this Family has **Kluang Series** as the central family member, then the soil is said to belong to the Kluang Family of soils.

46. As indicated earlier (slide 22), the amount of **information in the soil name** increases from the Order level to the soil series. This and the following slides illustrate this. At the Order level, the term Oxisols implies a few properties of the soil.

47. The **Suborder**, USTOX, has additional information attached to the name.

48. The **Great Group,** KANDIUSTOX, has many more properties. They become more specific when the soils are classified at lower categoric levels.

49. The **Subgroup** names have other properties attached to it as shown on the slide.

50. Finally, the **Family name** adds more information. Thus, by arriving at the Family level of classification, a whole range of properties can be inferred from the soil name. This is one of the advantages of the nomenclature of *Soil Taxonomy* which is absent in most other classification systems. It is now possible to give a name to a soil based on its properties and, equally important, dissect the name and derive the properties from the name.

MODULE IV

51. FORMATION AND LANDSCAPE RELATIONSHIPS

Soil formation is the cumulative effect of the factors of soil formation (Jenny, 1941). Each of the factors control processes which operate simultaneously, successively, or the products of one set of process may trigger another process/es. The soil we see today is in a steady state with the processes. It is important to note that some of the properties may have been determined by processes of an earlier period. Due to climatic or local changes in physiographic conditions, new sets of processes may be initiated or former processes may be terminated *and their products preserved as relics or eradicated by the results of current processes. Aspects of this will be illustrated in the section on soil micromorphology.*

With respect to the nature of the parent material, Oxisols may develop directly on the weathering product of the rock (autochtonous) or formed on transported sediments which are usually preweathered (allochtonous). In terms of extent, the latter is more prevalent than the former. Oxisols on the Brazilian and Guayanian Shields and the Central African Plateau are formed on mid- to end-Tertiary surfaces. They are generally deep as the sediments are deep. The concept of soil and parent material (the latter being defined as the weathering product of rock) is not applicable in such situations.

In this module, only some general concepts are presented. Other aspects, such as mineral alteration, are considered in other modules.

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52. The slide shows a diagram illustrating the classic factors of **soil formation**. A factor which is more important in the formation of Oxisols than in many other kinds of soils is the geomorphic evolution of the landscape. Landscape genesis determines many of the soil characteristics and may have a greater influence in determining the properties of the soil than the other factors of soil formation.

53. Weathering of a rock is a first step leading to soil formation. In the slide, basalt shows **exfoliation** (onion structure) due to weathering. The foliation is caused by temperature and moisture changes during the year. Other rocks may show other morphological changes upon weathering.

54. On old landscapes, landscape deformation is an important process. On sloping land, soil creep displaces the soil. The slide shows a quartz vein being dislodged and broken up leading to the formation of a **stone-line**. Stone-line formation, more frequently, results from geologic erosion and deposition. Stone-lines frequently suggest that the soils are formed on transported deposits and points to the allochtonous nature of the material.

55. The diagram illustrates an **allochtonous** (transported) and **autochtonous** (in situ) profile. The former frequently has stone-lines while the latter shows the classical sequence of horizons — soil-saprolite-rock — with no interruptions or discontinuities.

56. Climatic and geomorphic processes are not the only processes operating to form or modify the soil. In the tropics, biological activity is very high. Due to the high surface temperatures, many organisms live below ground. The **termite nest**, seen in the slide, is characteristic of semi-arid landscapes in the tropics. Termite activity homogenizes the soil and frequently erases the products of soil formation, such as cutans or clay skins. Termites also transport organic matter from the soil surface to deep layers in the soil where decomposition is much slower. Many soils of the tropics, particularly Oxisols, have much higher amounts of soil organic carbon than their counterparts in temperate regions.

In the earlier section, the geomorphic evolution of the landscape is emphasized. The landscape provides clues not only on the genesis of the soil but also the factors that control the processes operating on or in the soil. A landscape assessment informs the soil scientist of the associated soils and aids in making management decisions. Studying a soil profile in great detail becomes less meaningful without appreciating the context of the soil in its landscape.

57, 58. Oxisols occur in a wide variety of landforms and climates. This slide from the semi-arid southwest of Puerto Rico shows an undulating topography with an ustic soil moisture regime. However, Oxisols can also form in more dissected landscapes as in the tropical rainforest in northeastern Puerto Rico which has a perudic soil moisture regime.

59. The slide shows an Oxisol (Nipe soil — **Anionic Acrudox**) from Puerto Rico formed on ultrabasic rocks (exposed on the left of the picture). The rock on the right of the picture is an andesitic rock and weathers to form a brown soil. The Nipe soil, which is dark red, can be seen moving downslope onto the brown soil. This process is called soil creep, which is not very evident in other soils.

60. **Peneplanation** results in slightly undulating or nearly level landforms as seen in the foreground of this landscape in Puerto Rico. This geomorphic surface is a remnant of the St. John Peneplain that has escaped erosion. Oxisols occupy the flat landforms. The faint skyline at the horizon represents c**oncordant hills** that mark the surface of the Tertiary peneplain that is now undergoing erosion and dissection.

61. The tops of the **concordant hills** have a rolling landscape as shown in this picture. The soils on the upper part of the low hills are Oxisols. Ultisols occur on the side-slopes, and towards the valleys, Inceptisols and Entisols are present. This is a view of the St. John Peneplain in Puerto Rico.

62. Landscape relations are shown in this diagram of Beinroth et al. (1974). The diagram illustrates an originally flat lava flow undergoing **dissection**. Erosion and dissection reduces the general level of the landscape. Accompanying this is the general cutting down of the drainage way, which effectively lowers the ground water-table. All of these processes affect the soil characteristics and properties.

63. This slide is another illustration of the **landscape relationships** of Oxisols (Beinroth et al., 1974). This sequence is in Hawaii where the kind of soil is a function of not only the slope but also the number, kind, and thickness of the pyroclastic layers (see slide 64) that is present. There are other landscape relation studies and the reader is referred to the papers of Lepsch and Buol (1974 and 1977) for a study in Brazil.

64. These soils in Hawaii formed on two generations of **pyroclastic materials**. The upper material is weathered to form an Oxisol. The buried material has Ultisol features.

MODULE V

65. Morphology

Oxisols show a range of colors, horizonation, and other special features. Those in cool highland areas generally have an organic rich surface horizon. The lowland Oxisols have a thin, light colored, organic surface horizon. The texture may vary from a sandy loam to a clay. A characteristic feature is that the structural elements are very weak; when such a ped is gently pressed between the thumb and fore-finger, the material collapses or the material fails abruptly. This is probably a good field indicator that the soil has an oxic horizon.

When there is a fluctuating ground water-table, mottles appear in the zone influenced by the water-table. If the soil remains saturated with water for long periods, reduction and removal of the iron results in a whitish horizon. Some soils have plinthite which may be due to current water fluctuations or may be inherited from a previous time period when the water-table was higher than present day.

The color of the Oxisol (Eswaran and Sys, 1970) is generally a function of the iron content in the original material or rock. The color is also related to the kind of iron minerals with goethite producing yellow colors and hematite, red colors. Presence of colloidal organic matter darkens the soil. Many Oxisols have stone-lines with the stones being quartz or petroplinthite gravel. Petroplinthite is also referred to as hard laterite. The stone-line is a mark of lithologic discontinuity indicating that the material above the line was deposited or formed at a different period from the material below. Some soils have multiple stone-lines.

Some Oxisols may have other diagnostic horizons. A sombric horizon which is dark colored is present in many Oxisols of Central Africa. Some Oxisols may have a subhorizon which may meet the requirements of an argillic horizon, with clay-skins and good structure. This horizon may be a buried horizon or may indicate a bisequual profile — two stages of pedogenesis.

In this module, a range of soils is illustrated to show some of the variations that can be expected in the field.

66. The slide shows a deep soil formed on Tertiary transported materials at Malacca, Malaysia. The top 2 m of the soil (**clayey-skeletal, oxidic isohyperthermic, Typic Hapludox**) is composed of transported petroplinthite which rests on weathered saprolite developed from shale. A large lateritic boulder is in the foreground.

67. This is a typical soil of Southern Kerala, India, showing a deep weathering profile with a thin cap of transported petroplinthite. The soil shows **the classical sequence** comprised of red and mottled clay, the pallid zone which is whitish and bleached, and the underlying saprolite rock. The land was uplifted during the Tertiary and subsequent to the uplift there was down-cutting of the drainage ways and a consequent lowering of the ground water-table. The plinthite and petroplinthite are relic features. After stabilization of the landscape, a new sequence of erosion and transport results in the present-day rounded hills with lateritic cappings.

68. A close-up view of the profile in slide 67. The upper part of the profile is composed of poorly sorted **petroplinthic gravel**. There is an almost abrupt contact with the lower zone composed of plinthite. The soil is a **Plinthic Haplustox** from Trivandrum, Kerala, India.

69. The slide shows an **Anionic Acrudox** from Kuantan, Malaysia. The soil is developed on basalt. The rock was K/Ar dated to 1.9 million years. The basalt is a tholeitic basalt with many quartz inclusions and so the soil material has a high quartz content. The yellow to brownish colors are due to the very high amounts of manganese in this soil (>1.5% MnO_2). A few drops of H_2O_2 on the soil causes it to effervesce. The oxic horizon extends from about 20 cm depth to more than 3 m.

70. This **clayey, kaolinitic, isohyperthermic, Xanthic Hapludox** from Manaus, Brazil (03° 08' S; 60° 01' W; 100 m) is an example of a yellow Oxisol. It is formed in Cretaceous/Tertiary sandy clay deposits.

71. This **clayey, kaolinitic, isohyperthermic Typic Eutrustox** from northwestern Puerto Rico is developed in pre-weathered Quaternary sediments and limestone residue.

72. This is the Sungei Mas series (**Anionic Acrudox**) from Malaysia. This is an example of an Oxisol developed from the weathering product of ultrabasic rock. The general slope in the area is about 12 to 18 %. The soil is under secondary forest and the area receives about 4,000 mm annual rainfall. Such soils have been referred to as 'chocolate soils' in earlier literature due to the characteristic colors. Free iron oxide content is about 35% Fe_2O_3 in the soil and organic carbon is about 2% (B horizon). Despite the high carbon content, CEC is low, the charge is net positive, permanent charge is low, and pH dependent charge is high. The green rock in the lower part of the slide is **serpentinite**.

73. This is the Halii series (**Anionic Acrudox**) from Hawaii. Previously, this soil was classified as a Gibbsiorthox. It has about 45% gibbsite and about 12 % Fe_2O_3 in the fine earth fraction. The soil is formed on volcanic ash and cinder materials and has a relatively high organic carbon content. The high gibbsite content will place it in the gibbsitic mineralogy class.

74. Oxisols at high elevations (> 1,000 m) in the tropics have a humus-rich surface horizon which may qualify for a **mollic or umbric epipedon**. The slide shows a **Humic Rhodic Eutrustox** from Rwanda. There is more than 16 kg of organic carbon to a depth of 1 m over an area of 1 m^2. These soils are better suited for low input agriculture than those of the lowland tropics which contain less organic matter. If rainfall is favorable, they have few constraints for production of grain and cash crops. At the high elevations in the tropics, pest and disease infestation is less than at lower elevations. For these and other reasons, the high elevation plateaus support some of the highest human population densities in the world. A typical farming system of central Africa is illustrated in the slide. Bananas are inter-cropped with maize; peanuts are in the foreground.

75. Another typical feature in the highland soils of Central Africa is the presence of the **sombric horizon** as shown in the slide. It is a subsurface dark colored horizon. The presence of this horizon makes the soil distinctive. The soil is a **Sombriudox** from Rwanda.

76. Although most Oxisols are deep, some are shallow. The next two slides illustrate this. This slide is of the Matanzas series (**Typic Eutrudox**) from Puerto Rico formed on weathering products of limestone. It is highly probable that the soil material is a mixture of direct weathering products and transported infilling of a microkarst landscape.

77. The Nipe series (**Anionic Acrudox**) of Puerto Rico is normally a deep soil. On side slopes, the rock or **saprolitic material** may come close to the surface as shown in the slide. The Nipe Series is similar to the Sungei Mas Series of Malaysia described earlier (see slide 72).

78. Oxisols do not form when there is insufficient rain for weathering. However, in some areas, such as in parts of Oahu, Hawaii, and north eastern Brazil, Oxisols are found with present-day aridic soil moisture regimes. These soils are developed in transported deposits that acquired oxic properties during previous weathering under more humid conditions. The slide is the Wahiawa series (**Typic Haplotorrox**) from Hawaii and land-use is irrigated pineapple. With high input management, the soils are very productive. However, as the soils are very friable and have high infiltration rates, leaching of nutrients (nitrates) and contamination of ground water should be expected in such soils and landscapes.

79. The slide shows the Chok Chai series (**clayey, kaolinitic, isohyperthermic Typic Haplustox**) from Thailand. The soil is developed on weathering products of granodiorite.

80. This is a **fine, mixed, isohyperthermic, Humic Rhodic Haplustox** from Planaltina, Federal District, Brazil (15^{o} 35' S; 47^{o} 43' W; 960 m).

81. This slide shows a **clayey, kaolinitic, isohyperthermic, Humic Haplaquox** from the Federal District, (15^{o} 35' 30" S; 47^{o} 43' 10" W; 950 m) Brazil. The Aquox frequently occur in narrow valleys adjoining better drained Oxisols of the uplands.

MODULE VI

82. PROPERTIES

Oxisols have properties which are shared with other soils and some which are unique to this group of soils. Some of the unique properties are incorporated in the definition of the categories of the Order. The references cited in this publication refer to a number of publications which elaborate on many of the properties. It is difficult to illustrate many of the properties, except perhaps those which relate to mineralogy and micromorphology. Consequently, many slides are included on the micromorphological properties of Oxisols. Summary slides are provided for other properties.

Sections about 30-micron thick of undisturbed soil material are studied under a polarizing microscope at magnifications of 10 to about 100. Under plain light, the soil shows its natural colors and some minerals demonstrate special optical properties such as pleochroism. Some minerals are opaque (such as magnetite) or isotropic (such as halite) and can only be seen under plain light. Organic forms are best identified under plain light. With plain polarized light, minerals exhibit special properties by which they are identified. Mineral aggregates, particularly those of clay or colloidal size, also show specific properties by which they are recognized. Other accessory tools are available for the specific identification of minerals under the microscope. Magnification is sometimes a constraint and so a Scanning Electron Microscope (SEM) is used to view objects at magnifications of 25 to 50,000. An electron microprobe provides elemental composition of the material being studied and other techniques add information for the assessment of the soil material. Normally and when available, a combination of techniques is used in the micromorphological study of soils. In the slide set, some examples of features one can encounter in Oxisols are provided.

83. **Gibbsite** is present as a secondary mineral in many Oxisols. Weathering of primary minerals releases Si and Al; Si is lost in the soil solution while the Al crystallizes as gibbsite and the most common product is gibbsite crystal nodules. The large whitish nodule on the slide (crossed polarized light, magnification X50) is composed of gibbsite. Voids are black in the micrograph and the void walls are coated with a thin lining of translocated clay (argillans). The cutans are probably relic features in this Oxisol.

84. The **gibbsite crystals** in the gibbsitic nodules of micrograph 83 are well crystallized as shown in this SEM micrograph taken at a magnification of X 2,500. The crystals are euhedral and twinning is common. Typically, gibbsite crystals are fine-silt-sized. In many Oxisols, there is usually more gibbsite in the silt than in the clay fraction. It is for this reason that in the definition of gibbsitic families, the amount of gibbsite is expressed on the fine-earth (< 2 mm) fraction.

85. Many different forms of **gibbsitic features** may be seen in thin-sections and their formation is not well understood. In this thin-section micrograph (X 80), the reddish brown and almost opaque material is the isotropic soil material. It is isotropic because of the presence of high amounts of iron (28% Fe_2O_3) in this Acrudox from Madagascar. The voids are black and the void wall is coated by a thin layer of gibbsitic crystals which are oriented perpendicular to the wall. This and the thin-section in slide 86 of another soil clearly establishes the fact that Al can move in the soil.

86. This slide is of a thin-section of a Bt horizon at about 3.5 m depth in a Haplustox from Ituri, Zaire. The large white or gray grains are quartz. The fine crystals in the micrograph (X 80) are **gibbsite crystals**. The yellow mass, almost in the center of the micrograph, is a zone of **illuvial argillans**. The veins of gibbsite can be seen to cut across the illuvial argillans indicating that gibbsite formation is a process subsequent to clay illuviation. Here is also a feature that shows that the veins are not formed merely by capillary rise as was shown in the case of runiquartz.

87. The other frequent mineral in Oxisols is **goethite**. The micrograph (X 100) is from a Haplaquox in Malaysia. The void wall is coated by bands of goethite crystals arranged in a concentric form. Such forms are frequent in wet soils.

88. In **plinthite** other forms of **goethite** and **hematite** are common. The yellow mass and veins in the micrograph (X 50) of plinthite from Venezuela is goethite. The hematite aggregates are present as reddish spherules embedded in the goethite mass. The white zones are the iron-free zones and are composed of kaolinite and quartz.

89. **Laterite** or **petroplinthite** shows characteristic forms in thin-sections. This thin-section (X 80) is of a lateritic brick referred to in slide 27. The matrix is composed of red hematite crystals clustered as aggregates. The white and yellow materials are kaolinite.

90. This slide shows a SEM micrograph (X 10,000) of **goethite crystal aggregates** in a petroplinthite fragment. The goethite crystals have a typical lenticular shape and appears welded together. This gives the petroplinthic material its strength. Both goethite and hematite have different habits and they show different crystal forms.

91. In most Oxisols, the **fabric** is homogenous without too many specific entities like those illustrated previously. This micrograph (X 80) is of a Kandiudox from Rwanda. It shows a thin lining of **ferriargillans** (yellow coatings on the void walls). The presence of the clay skins is evidence of the transitional nature of the soil and that clay illuviation and accumulation was an important process. The transitional nature is indicated by the 'kandi' prefix in the soil name.

92. This micrograph is of the Bo horizon of the Chok Chai series from Thailand (see slide 79). The matrix is uniformly red indicating little reorganization of the iron. The white mineral is silt-sized quartz. There is no differentiation of the fabric in this Haplustox.

93. This micrograph is at a magnification of X 100. The **plasma** within the aggregates is very homogenous and is composed of an intricate mixture of **kaolinite** and **iron oxyhydrates**.

94. When the same feature in slide 93 is observed at a higher magnification (X 150), the **plasmic material** appears spongy. It is also hydrophobic and repels water and so the aggregates are not wetted easily. Water retained at tensions of 1/3 and 15 bar show that the available water holding capacity of this soil is very low, < 25 mm per 100 cm of soil. The measured clay in this soil is 65% and the anomaly with respect to water holding capacity is due to the very low specific surface area.

95. The surface horizon of Oxisols have a relatively high organic matter content, unless eroded. Biological activity is high. A SEM study (X 10,000) of such a surface horizon shows the presence of **fungal hyphae** and fruiting bodies. Fungi and mycorrhiza are generally indicators of good soil quality.

96. The drier tropics are also typified by the presence of large **termite nests** which can reach 5 m in height. There are species of termites which are subsoil dwellers and termite galleries may go several meters into the soil. Bioturbation of the soil is an important soil forming process in tropical soils.

97. Oxic B horizons have a friable consistency. When a large chunk of soil is gradually crushed in the hands, the soil material breaks down and fine rounded bodies are left behind. Belgian pedologists, working in Africa, used to call this "Variole," meaning the soil has chicken-pox. They only observed it in Oxisols. These are referred to as '**pedovites or soil eggs**'. Their origin is not established. The slide shows pedovites from the Kuantan series in Malaysia (see slide 69).

98. The very good and stable structure of Oxisols and their rapid infiltration rates, makes them **resistant to erosion**. In fact, steep slopes and road banks are usually stable and these are generally indicators that the soils in the area are Oxisols. However, misuse of these soils can result in accelerated erosion and experiments, as shown in the picture, are being conducted to determine rates and processes.

Summary statements are provided for the other properties of Oxisols.

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99. Summary of morphological properties I

100. Summary of morphological properties II

101. Summary of physical properties I

102. Summary of physical properties II

103. Summary of mineralogical properties I

104. Summary of mineralogical properties II

105. Summary of chemical properties I

106. Summary of chemical properties II

MODULE VII

107. GLOBAL EXTENT AND GEOGRAPHIC DISTRIBUTION

Absence of reliable national maps in many countries of the world prevents an accurate assessment of the extent and distribution of Oxisols. The only map available for such assessments is the Soil Map of the World (FAO-UNESCO, 1971-1976) which has been digitized by FAO. This digitized vector map was converted from the FAO legend to Soil Taxonomy *units, a process which also involves many sources of errors. The FAO map was developed during* *the sixties and since then, more reliable information is available for a few countries, specifically for Brazil. As the digital map is vector based, the new information cannot be incorporated unless FAO develops a new vector map. Thus, the area of Oxisols presented here is probably considerably overestimated. It is not only overestimated in Brazil, but also in the northern part of the Southern African Plateau. Finally, in the last two decades both Soil Taxonomy and the Legend of the Soil Map of the World have undergone many revisions, which introduces other sources of errors in the current estimates.*

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108. To place the distribution of Oxisols in its proper perspective, the first global map presented here is that of the soil moisture regimes (SMR). The tropics, for convenience, is the zone between the Tropics of Cancer and Capricorn. By definition, there is no xeric SMR in this zone which contains all the other SMRs.

109. The slide shows the global distribution of the soil temperature regimes (STR). The tropics are characterized by 'iso-' STRs. As will be shown later, the Oxisols, though dominant in the iso-STRs, also extend into the non-iso thermic STR as in Southern Brazil.

110. Over 90% of the Oxisols occur in the tropics. South America and Central Africa have large contiguous areas of Oxisols. In South East Asia, the distribution is localized and generally confined to those areas with basic rocks. In S. America and C. Africa, the Oxisols are found on old geomorphic surfaces and developed on pre-weathered and transported sediments. These are referred to as allochtonous Oxisols. In S.E. Asia and the Pacific Islands, many of the Oxisols are formed from the weathering products of the underlying rock and are referred to as autochtonous Oxisols.

111. Oxisols are geographically associated with Ultisols in the tropics. This map shows the distribution of Ultisols.

112. S. America has the largest contiguous extent of Oxisols, with Brazil having the largest area. The western extent of the Oxisols shown on the map is in error. Recent soil survey activities in this part of Brazil and Peru shows that the soils are Ultisols and not Oxisols. Corrections will be made in future global maps.

113. Zaire has probably the largest extent of Oxisols in Africa. New surveys in Zambia suggest that the extent indicated in the FAO-UNESCO Soil Map of the World is probably in error.

114. In S.E. Asia, Oxisols are present in small isolated areas. Probably the largest area is in Borneo (Kalimantan) but even this is yet to be verified.

115. The slide shows the distribution of soil orders globally. The area is expressed as thousands of square kilometers. The table includes the recently established order of Gelisols, which effectively reduced the area of the other orders.

116. The pie chart shows the relative areas of the Suborders of Oxisols. Ustox are the most extensive and occupy over 50% of the Oxisol area. The Aquox occupy just under 3% while the extent of Torrox is about 0.3%. Most of the Torrox are in Brazil with a very small area in Hawaii.

117. Over 98% of the Oxisols are found in S. America and Africa. S. America has more than 57% of the Oxisols of the world.

118. The slide shows the relative distribution of the Oxisols in the three continents.

MODULE VIII

119. Use and Management

The highly weathered soils of the tropics, specifically the Oxisols, have been perceived as being problematic for management and unproductive. It is true that they have many constraints but under high levels of management and particularly for perennial crops, their productivity is economic and sustainable. They of course share many of the management problems of other soils and in some, such as moisture stress, they are more severely impacted than for example some Alfisols. Under low-input agriculture, productivity is low, risk is high, and potential for resource degradation is also high. In this module, aspects of management are considered with illustrations of how to address some of the more important constraints.

Due to inherent difficulties of low-input agriculture, which traditional farmers are usually aware of, Oxisols were not exploited for large scale cultivation until recently. This is despite the fact that the land surface, tillage conditions, and other properties appear attractive for cultivation. In fact, these same features prompted much early research on the management of the soils. There are still many misconceptions of the management properties of these soils, one being that they share similar yield constraining properties of other acid soils. There are a few members of Oxisols which have soil acidity and aluminum toxicity as a dominant constraint. Oxisols in general are not restricted by acidity and few have Al problems. However, that does not mean that they do not respond to liming. The response is due to the amendment and nutritional effect of the calcium and not to neutralizing effect of soil acidity. Thus there are some fundamental differences in management of Oxisols as compared to other soils, and this must be borne in mind.

120. **Plinthite** and **plinthic materials** are sources of **engineering materials** in many countries. In a country which has practically no stones for construction, such as Bangladesh, plinthic materials are oven-baked and used as stones for road building. The slide shows plinthite being cut out in Kerala, Southern India, for making bricks.

121. The **plinthite bricks** are sun-dried and become very hard. Occasionally they are oven-baked. On drying, the iron minerals, such as goethite and hematite, form a strong cement and hold the material together.

122. Traditionally, **plinthite bricks** have had many uses and many **historic buildings** made of this material still stand today. The slide shows a Portuguese fort built in 1511 in the town of Malacca, Malaysia. The fort not only withstood the climate but also the wars between the various colonial powers who needed it to control the Straits of Malacca. In the State of Karnataka, India, tombstones dating back to 600 years and made of laterite have been found. In fact, plinthite was such an essential building material that there are few areas in the western part (the piedmont of the Western Ghats) of India which have not been excavated and reworked.

The high aggregate stability, generally good internal drainage, and favorable landscape makes Oxisols less erodible than other soils. Under natural vegetation, erosion is minimal. With improper management, the soil is subject to erosion just like any other soil. The effort required by farmers to minimize erosion is less than most other soils and even under low-input agriculture, soil degradation can be contained.

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123. Large scale **land clearing**, as in Brazil, Indonesia and Malaysia is frequently done with heavy machinery. The timber-tracks as shown in the slide become the main arteries for land-settlers to invade the land. Land clearing is the first cause of land destruction in these tropical forest areas. Further soil degradation ensues after the forest undergrowth is burnt and the land is cleared for agriculture. The slide is from Acre State, Brazil, where a pasture of Brachiaria is being established. A few Brazil Nut trees are the only remnants of the former forest.

124. Sheet erosion is not readily apparent on the field but **gullies**, as shown in this slide from the savanna region near Brasilia, Brazil, are ample evidence that erosion is active in this landscape. Soil erosion caused by land clearing has removed the top soil in the area and with this all the sustaining nutrients are also gone. If these nutrients are not replenished, the soil becomes non-productive very quickly.

125. The slide demonstrates the consequence of large scale land clearing. The slide shows the **Iguassu Falls** at the border of Argentina and Brazil. The water is red due to the very high **sediment load** resulting from land clearing activities in Brazil.

126. A scene similar to slide 125, is seen in this photograph of the Blue Water Falls in Kenya. The picture was taken in 1992 and the water was loaded with **sediment**. The second author had visited the falls in 1982, when the water was really 'blue.'

127. Pressures of modern society are frequently the root cause for **resource exploitation**. The picture shows intensive tomato cultivation on sloping Oxisols, near Rio de Janeiro. The land form is not suitable for this type of cultivation. The farmers are aware of this but would rather make a 'quick-buck' when the price is right than invest in other technology.

128. A **gully** formed by rill erosion (at the same area in slide 127) is developing at the point where the irrigation and rain water is seeking a channel to move downslope. Sheet erosion is also rampant and this piece of land had to be abandoned after two or three crops.

129. Even if the land is abandoned, the consequence of misuse is not over. **Land-slips** and **landslides** continue for a long time. Because top soil is gone, vegetation cannot reestablish and so erosion continues until bare rock is exposed. The slide was taken in the same area as slides 127 and 128 near Paty do Alferes near Rio de Janeiro, Brazil.

130. Under plantation or cash-crop forms of agriculture, farmers make investments in some form of soil conservation practices. This picture is from Londrina, Parana State, Brazil, where corn was planted as an **inter-row crop** with coffee. The corn is harvested but the straw has been plowed in leaving the soil surface susceptible to erosion.

131. In an adjoining area in Londrina, the farmer practices **no-till soybean** after a preceding crop of wheat. This system of crop production, which is increasingly being practiced in Brazil, keeps the soil well protected against heavy rainfall, thus diminishing problems of soil erosion.

132. Due to the nature of the colloid aggregation, **soil compaction** is not easily achieved and was also not a major problem in many Oxisols. However, due to introduction of heavier machinery, compaction results, as shown in the slide. Clayey soils with low sesquioxide content are more prone to compaction.

133. Hand-clearing procedures for land clearing, though not as efficient as mechanized clearing, are generally less taxing on the soil. This method is sometimes referred to as **'slash and burn,'** as shown in the picture from Cameroon. The vegetation is allowed to dry out and then it is burned. The ash that accumulates on the soil is a concentrated source of nutrients. The emission of carbon dioxide to the atmosphere contributes to global warming and this is one of the negative consequences of burning.

134. After a complete **burn** there are still stumps and large logs on the ground. These will take a few years to rot. In the meantime, the farmer has his first crop of upland rice as shown in the picture taken along the Trans-Amazon highway between Itaituba and Altamira Counties, Para State, Brazil.

135. Depending on the country and region, the second and successive crops vary. In the Amazon region, **pasture establishment** is a general practice. In southern Brazil, wheat is planted as shown in this picture from Cascavel, Parana State, Brazil. After harvest, the straw is burned. Farmers believe that burning provides the nutrients and reduces insect pests and also weeds. Burning also facilitates subsequent soil tillage.

136. Establishment of a good crop on Oxisols requires good **nutrient management**. Nutrients must be applied in small amounts and periodically to counteract leaching losses and fixation. This is particularly true for phosphorous as shown in the picture. In the absence of P, as in the foreground, the maize does not grow.

137. In addition to nutrients, **water** is the other essential input. Hawaiian sugarcane plantations receive drip irrigation to provide the moisture needed for growth. Oxisols are sometimes referred to as 'droughty' soils as they suffer from moisture stress earlier than other adjoining soils.

138. On a Eutrustox in Puerto Rico, up to 10,000 kg/ha of maize have been produced under optimum water and nutrient management conditions.

A large range of crops are grown on Oxisols. Examples are shown in the following slides and, where possible, aspects of management are presented.

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139. Plantations of **rubber** (*Hevea brasiliensis*) are the most profitable land use on Oxisols in Malaysia and some other S.E. Asian countries. The rubber tree with an economic life of 35 or more years is adapted to the low nutrient content soils. It does best on soils with udic soil moisture regimes; from a plant physiology plant of view, a perudic SMR is also desirable. However, as tapping of the tree is done in the morning, the rainfall pattern should be such that the rain is during the late afternoon or at night. If rain occurs after tapping, the latex is washed out of the tapping cut and does not accumulate in the collection cups. The tree is very susceptible to moisture stress. Yield decline commences after more than a few days of moisture stress. The ustic SMR is not suitable for rubber though it is grown under such SMRs in southern India and West Africa.

140. Young **rubber** is planted on contour terraces and a cover crop (*Centrosema pubescens* or *Pueraria spp*.) is planted for soil conservation purposes. The slide shows a typical rubber plantation in Malaysia. The houses of the workers are strategically placed around the plantation for ease of transit.

141. **Oil-palm** (*Elaeis guinensis*) is also grown on Oxisols. It does very well on moderately to poorly drained soils and Oxisols are not the best soils for oil-palm. Oil-palm also requires better nutrient supply and, like rubber, is susceptible to moisture stress. When there is moisture stress, the fronds droop as shown in the slide.

142. This slide shows mature **oil-palms** in a plantation of about 12 years. Cover crops are maintained as in rubber plantations. The cover crops die out when the canopy of the palm closes and cuts out the light. Decay of the cover provides nitrogen and other nutrients to the feeder roots of the rubber tree or oil-palm.

143. A crop that adapts to low nutrient and soil moisture stress conditions is **pineapple** (*Ananas sativus*). This is a pineapple plantation at the north coast of Puerto Rico. Though the crop requires moisture stress at maturity of the fruit, during the vegetative growth stage, supplementary irrigation ensures a good crop.

144. It is significantly more risky to grow **annual crops** on Oxisols. Many of the resource poor farmers of the tropics, who have to live on Oxisols, have to be supported and so research is conducted by national and international institutions around the world. The slide shows experiments at Isabela, Puerto Rico, evaluating the nutrient and moisture requirements of many food crops.

145. Understanding the **moisture variability** in this unique soil has been a challenge for many soil scientists and agronomists. **Piezometers** in the soil are monitored daily to provide data which are then used in a model to evaluate moisture supply and retention patterns. This slide illustrates the work of a USAID funded project in Jaiba, Minas Gerais, Brazil.

Brazil has the largest extent of Oxisols. The next set of slides illustrates land use on Oxisols in this country. Examples from low-input colonizing agriculture to large scale plantation type management are provided.

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146. The shifting cultivator opens small (less than 0.25 ha) tracts of land to establish his farm. The slide shows a **cleared tract of land** in Itaituba, Para State, Brazil. The clearing is done with machete and burning.

147. A range of crops is planted in the first season after clearing. The photograph taken along the Trans-Amazon Highway between Itaituba and Altamira in Para State shows an **inter-cropping** of cassava with maize. All kinds of combinations of crops may be seen along the highway.

148. Within a year or two, beside the plot of land with food crops, the farmer sets up a pasture. The picture, taken in Assis, Acre County in Brazil, shows **degraded pasture**. Cattle is an important component of the farming system in this part of the country.

149. Once the farmer is established on the land, he starts to plant perennials. The picture shows a stand of **babacu palm** (*Orbygnia martiana*) which is a native palm of the northeastern part of Brazil. The nuts are used as food, or oil is extracted for use as a lubricant in precision machinery. The fronds and trunk can be used for fuel.

150. In Yurimaguas, Peru, farmers plant the **peech palm** (*Guilierma especiasa*) which produces a very nourishing drink and food. Cattle is kept under the palms and the cover crop is maintained for the cattle.

151. **Papaya** (*Carica papaya*) and other crops are grown for cash on the Oxisols of Peru. If a market is readily available, papaya is an excellent cash crop for Oxisols. With some supplementary nitrogen and phosphorous fertilizers, it is a lucrative crop.

152. Apart from food crops, a whole range of economic crops can be grown in the tropics. The slide shows an **anatto plantation** in Belem County, Para State, Brazil. The red fruit of Annatto (*Bixa orellana*) produces a dye used in the cosmetic industry.

153. In the Amazon jungle, an important second story crop is **gurana** (*Paullinia cupania*) which produces bright red fruits, the size of cherries. Each fruit contains a large number of seeds which is ground to a paste and used for medicinal purposes. The pulp is also squeezed for a drink which has a very high ascorbic acid content. (Locally, gurana juice is spiked with vodka or other alcoholic beverages which results in a refreshing drink that is said to make life easier in the hot, humid, insect-ridden tropical forest.)

154. **Mango** (*Mangifera indica*) is a good cash crop. The quality of the fruit improves in areas with prolonged moisture stress (ustic SMR).

155. Another secondary story crop in the tropical jungle is **cacao** (*Theobrama cacao*) which is now successfully cultivated in plantations. The ripe pod is split open and the large chestnut-sized seeds covered with mucilage is scraped out and stored in a box for fermentation. After fermentation, the seeds are cleaned, dried, and powdered for chocolate making.

156. Cropping systems vary with the climatic endowments of the land. Soybean is an important crop in the thermic soil temperature regime areas. The picture shows a farm with **cassava** (*Manihot utilissima*) in the foreground and **soybean** (*Glycinia max*) in the background in Londrina, Parana State, Brazil.

157. Complex **inter-cropping systems** can be seen as farmers attempt to reduce their risks. The picture shows such a system. Maize is planted 20 days after common beans, which is an inter-crop. After the harvest of beans, oats are the subsequent crop. Later, the maize is manually harvested and the stalk is used as support for a later pea plant. This is an example of multiple cropping at its best.

158. This is an example of inter-cropping of **coffee** (*Coffea arabica*) with **rice** (*Oriza sativa*). The 2.5 year old coffee is intercropped with three rows of rice. Inter-cropping is done until the coffee is about 5 years old. In the last year of the inter-crop, the rice may be replaced with a bean crop.

159. **Mulching** is a common land management practice in **coffee plantations**. The 6-year old coffee was planted with **mucuna preta** (*Stizolobium aterrimum*) which is used as green manure. The mulch also helps to conserve the soil moisture. The mucana plant further has nematocoidal properties.

160. This is a close-up of the **mucuna mulch plant** (*Stizolobium aterrimum*). This legume is capable of fixing 150 kg of N per hectare per year and also offers good protection against raindrop splash erosion.

161. Summary of fertility and management related properties I

162. Summary of fertility and management related properties II

MODULE IX

163. Sustainable Development Considerations

The humid tropical forest ecosystem, with Oxisols as the dominant soil, is a pristine environment and serves as an enormous reservoir of sequestered carbon, biological diversity with a wide array of plants and animals, in addition to being a resource of food, timber, medicine, and other products for people. Plantation agriculture with localized small farmer use did minimal disturbance to the natural equilibrium. With population increases, the fragility of the ecosystem is being tested. Over 15 million hectares of forests are now being destroyed annually with little or no effort to regenerate. Resilience of such ecosystems is so low that complete regeneration may not be achieved. In addition, some plants and animals adapted to unique niches in this ecosystem are lost permanently when their habitat is destroyed. Although there are many attempts, particularly in the Amazon Basin to understand the system, there are few efforts to develop remedial measures to reduce the negative impacts.

The limited resource farmers of the tropics, who are the silent majority in this ecosystem, practice shifting cultivation and their sheer numbers have made the slash-and-burn form of agriculture the most extensive form of agriculture in this ecosystem. The consequence is that forests are decreasing in area, forest resources are decreasing in amount and composition, and in the process of performing this form of agriculture the farmers are not only reducing the quality of the resource base but also impacting the quality of the global environment, primarily through the release of carbon dioxide and other greenhouse gases. The challenge is then to develop a viable alternative to the slash-and-burn form of agricultural system. If successful, the rewards are not only to provide a mechanism for the millions of people to extricate themselves from the poverty trap they are in today but also to ensure the survival of the forest ecosystem and reduce the negative environmental impacts that are already well entrenched.

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164. As shown earlier, large areas of Oxisols of the world are still under forest. The hostile environment of the tropical forests helped preserve and protect them from human onslaught. However, due to pressures on land resulting from the ever-increasing population, they have become a new frontier to conquer. **Forest fires** now light the skies of the humid tropics, destroying biodiversity, and increasing the atmospheric carbon dioxide.

165. The slide shows a two year old **pasture** in the foreground and new forest being cleared in the background.

166. Tropical forests yield a number of forest products. The picture shows **cane rattan** being harvested for furniture making. Rattan furniture is popular in the tropics because it is not eaten by termites.

167. Other forest products include **fuel wood**. Difficulties in obtaining fuel for cooking and other household uses is one of the factors that lead to slow deforestation. This picture from Pucalpa, Peru, shows boys harvesting wood for sale. Agroforestry can be developed to provide the necessary wood and this could reduce the pressures on the forest ecosystem.

168. In the great plains of Africa, **wildlife** is under threat as populations compete for land. Some countries, like Kenya, have established national parks to protect this biodiversity. In others, poaching is a way of life. Rhinos are endangered because their horns have medicinal value. The elephant is hunted for its ivory tusks.

169. Zebras and other wild animals are being stressed as **wildlife** refuges become reduced in size. These animals have adapted to the ecosystem. The wild-life areas have a range of soils, each with its own animal population supporting capacity. Competition for the good land for agriculture relegates the poorer land to wild animals and this is also an indirect impact on biodiversity.

170. Sustainability and environmental considerations I.

171. Sustainability and environmental considerations II.

172. These children may suffer because of our lack of understanding of the soil resource base.

173. Concluding statement I.

174. Concluding statement II.

175. Concluding statement III.

Concluding Remarks

In 1993, the global distribution of food amounting to about 17 million tons (or about $4 billion worth) was a record for the transfer of food from industrialized to developing countries. Much of this was in response to national crises as in Somalia, Rwanda, and a few of the former Soviet countries, while the remaining was mainly to support weak economies. In an analysis of such assistance, Webb (1995) indicates that the total distributed was about 50% of the actual requirements of these countries, and also that in 1994, there was a decline (14 million tons) and further that with economic constraints in many of the industrialized countries, the decline may increase.

Although self-sufficiency in food and fiber production is the stated goal of practically all countries of the world, the magnitude of food-aid suggests that many countries do not have the capability and/or technology to meet this goal by the year 2020. To attain some semblance of sufficiency will require an annual rate of growth in yield of major cereals of about 1.5 to 2 percent. For some countries, this rate has to be much higher. This is a major challenge which appears insurmountable for various reasons. The world food crises of 1973 drew attention to the delicate balance of the food supply situation and there was much apprehension for the immediate future. However, the situation changed in the eighties with surpluses being produced by many industrialized countries and with a concomitant drop in prices. With a more constrained budgetary situation in the industrialized countries, the nineties saw drastic reductions in support for international agricultural research and development activities. The focus on environmental concerns and the commitment to produce a healthier environment has been at the expense of productivity increases. The situation is serious enough to warrant a comment by FAO (1993) that by the year 2010, many developing countries that were hitherto net exporters will have become net importers of agricultural products.

The physical limits of the land resource base was known even to the earliest societies. But the notion of the ability of the land to feed and clothe the population is only recently being widely appreciated. In addition, the ability of the land to perform its functions (in addition to producing food) is also being continuously reduced. These functions include partitioning precipitation into infiltration and runoff, biochemical cycling of organic materials and buffering against rapid changes in the habitat provided by soil for roots and organisms. Apart from assessing the productivity of the land, there is now a demand for determining how well soils perform ecological functions, such as rate of cycling, buffering against pollutants and rapid changes in water content and temperature, and infiltration to limit erosion and improve water quality.

Oxisols, are in a sense the last frontier for conquest of land in the tropics. Their generally favorable topographic attributes and the advances in soil management technology have made them candidates for agricultural expansion. Oxisols now support the largest extent of tropical forests and so any conversion to agricultural land will be at the expense of forests, biodiversity, and the consequent impacts on global climate. Understanding these soils helps to protect the environment and at the same time makes agriculture sustainable.

BIBLIOGRAPHY

(Publications of the International Committees on Classification are highlighted)

Alexander, L.T. and Cady, J.G. 1962. Genesis and hardening of laterites in soils. USDA Tech. Bull., 1282, 90 pp.

Aubert, G. 1958. Classification des Sols. Compte Rendu, Reunion Sous-comite, Congo Brazzaville.

Bennema, J., R.C. Lemos, and L. Vetturs. 1959. Latosols in Brazil. IIIrd. Inter-African Soils Conference, Dalaba. I:273-281.

Beinroth, F.H., G. Uehara, and H. Ikawa. 1974. Geomorphic relations of Oxisols and Ultisols on Kauai, Hawaii. Soil Sci. Soc. Amer. Proc. 38:128-131.

Beinroth, F.H. and S. Paramanathan. 1978 (Eds.) 1978. Proceedings of Second International Soil Classification Workshop. Part I, Malaysia. Publ. Dept. Of Land Development, Bangkok, Thailand. 344 pp.

Beinroth, F.H. and S. Panichapong. 1978 (Eds.) 1978. Proceedings of Second International Soil Classification Workshop. Part II, Thailand. Publ. Dept. Of Land Development, Bangkok, Thailand. 429 pp.

Beinroth, F.H., J.A. Silva, R.W. Arnold, and F.B. Cady. 1980. Agrotechnology transfer in the tropics based on Soil Taxonomy. Adv. Agronomy. 33:303-339.

Beinroth, F.H., H. Neel and H. Eswaran (Eds.). 1983. Proceedings of the Fourth International Soil Classification Workshop, Rwanda. Part 1: Papers (518 pp.); Part 2: Field Trip Background and Soil Data (175 pp.). Agric. Editions 4, ABOS-AGDC, Brussels, Belgium

Beinroth, F.H., M.N. Camargo, and H. Eswaran (Eds.). 1986. Proceedings of the Eighth International Soil Classification Workshop: Characterization, Classification, and Utilization of Oxisols. Brazil Publ. EMBRAPA-SNLCS, Rio de Janeiro, Brazil. 285 pp.

Bonifas, M. 1959. Contribution a l'etude geochimique de l'alteration laterique. Mem. Serv. Geol. Alsace-Lorraine, 17, 159 pp.

Botelho da Costa, J.V. 1954. Sure quelques questions de nomenclature des sols des regions tropicales. Compte Rendu Conf. Int. Sols Africains, Leopoldville, Congo. 2:1099-1103.

Botelho da Costa, J.V. 1959. Ferralitic, tropical fersiallitic and tropical semi-arid soils: definitions adopted in the classification of the soils of Angola. IIIrd. Inter-African Soils Conference, Dalaba. I:317-319.

Brewer, R. 1964. Fabric and Mineral Analysis of Soils. Wiley, New York, N.Y. 470 pp.

Buchanan, P. 1807. A journey from Madras through the countries of Mysore, Kanara and Malabar. East India Co., London, 2:436-461.

Buol, S.W. and H. Eswaran. 1978. Micromorphology of Oxisols. In: M. Delgado (Ed.), Proc. Vth. Int. Work. Meet. on Soil Micromorphology, Granada, 325-328.

Buol, S.W., F.D. Hole, and R.J. McCracken. 1980. Soil Genesis and Classification. Iowa State University Press. 404 pp.

Buol, S.W. and H. Eswaran. 1988. International Committee on Oxisols: Final Report. Publ. Soil Management Support Services, Technical Monograph No. 17. 157 pp., Washington D.C.

Camargo, M.N. and F.H. Beinroth (Eds.). 1978. Proc. First International Soil Classification Workshop. Publ. EMBRAPA-SNLCS, Rio de Janeiro, Brazil. 376 pp.

Charter, C.F. 1958. Report on the environmental conditions prevailing in Block A, Southern Province, Taganyika Territory, with special reference to the large-scale mechanized production of ground-nuts. Ghana Department of Soil and Land Use Survey, Occasional Paper 1, 37 pp.

Cline, M.G. 1949. Basic principles of soil classification. Soil Science, 67:81-91.

Cline, M.G. 1963. Logic of the new system of soil classification. Soil Science, 96:17-22.

Cline, M.G. 1975. Origin of the term Latosol. Soil Sci. Soc. Amer. Proc., 39:162.

Daniels, R.R., H.F. Perkins, B.F. Hajek, and E.E. Gamble. 1978. Morphology of discontinuous phase plinthite and criteria for its field identification in the Southeastern United States. Soil Sci. Soc. Amer. J. 42:944-949.

El Swaify, S.A. 1980. Physical and mechanical properties of Oxisols. In : B.K.G. Theng (Ed.) Soils With Variable Charge. Publ. Soils Bureau, DSIR, Lower Hutt. New Zealand. 303-324.

Eswaran, H. and N.G. Raghumohan. 1973. The micro-fabric of petroplinthite. Soil Sci. Soc. Amer. 37:79-81.

Eswaran, H., G. Stoops and C. Sys. 1977. The micromorphology of gibbsite forms in soils. J. Soil Sci. 28:136-143.

Eswaran, H. and C. Sys. (1970). An evaluation of the free iron in Tropical basaltic soils. Pedologie, 20: 62-85.

Eswaran, H., C.H. Lim, V. Sooryanarayanan, and N. Daud. 1978. Scanning electron microscopy of secondary minerals in Fe-Mn glaebules. In (Ed. M. Delgado), Proc. Vth. Inter. Work. Meet. Soil Micromorphology, Granada, Spain. 851-866.

Eswaran, H. and R. Tavernier. 1980. Classification and genesis of Oxisols. In: B.K.G. Theng (Ed.), Soils with Variable Charge. Publ. Soils Bureau, DSIR, Lower Hutt, New Zealand. 427-442.

Eswaran, H., H. Ikawa, and J.M. Kimble. 1986. Oxisols of the world. In: Proceedings of the International Symposium on Red Soils. Publ. Science Press, Beijing, China. 90-123.

FAO-UNESCO, 1971 - 1976. Soil Map of the World. FAO, Rome, Italy.

FAO, 1993. Agriculture Towards 2010. Publ. for the 27th. Session, Rome.

Grossman, R.B., R.H. Rust, and H. Eswaran (Eds.). 1984. Soil Taxonomy: Achievements and Challenges. Soil Sci. Soc. Amer. Special Publ. 14. 76 pp.

Harrassowitz, H. 1930. Boden der Tropischen Region. Laterit und allitischer Rotlehm. E. Blanck's Handbuch der Bodenhehre. Berlin. Vol. 3:387-536.

Harrison, J.B. 1933. The katamorphism of igneous rocks under humid tropical conditions. Imp. Bur. Soil Sci., Harpenden, 79 pp.

Herbillon, A. 1980. Mineralogy of Oxisols and oxic materials. In: B.K.G. Theng (Ed.), Soils with Variable Charge, New Zealand Society of Soil Science, Lower Hutt, New Zealand. 109-126.

Jenny, H. 1941. Factors of Soil Formation. McGraw Hill, New York, 281 pp.

Lepsch, I.F. and S.W. Buol. 1974. Investigations in an Oxisol-Ultisol toposequence in Sao Paulo State, Brazil. Soil Sci. Soc. Amer. Proc. 38:491-496.

Lepsch, I.F., S.W. Buol, and R.B. Daniels. 1977. Soils-landscape relationships in the Occidental Plateau of Sao Paulo State, Brazil. Soil Sci. Soc. Amer. J. I, 41:104-109; II, 41:109-115.

Maignen, R. 1966. Review of Research on Laterite. UNESCO Paris, 148 pp.

Marbut, C.F. 1935. Soils of the United States. In: USDA Atlas of American Agriculture, III. 11-16. US Govt. Printing Office, Washington D.C.

Moormann, F.R. 1985. Excerpts from the Circular Letters of the International Committee on Low Activity Clay Soils (ICOMLAC). Soil Managenment Support Services, Technical Monograph No. 8. Washington D.C.

Robinson, G.W. 1951. Soils: their Origin, Constitution, and Classification. Thomas Murby & Sons., London. 573 pp.

Ruhe, R.V. 1956. Landscape evolution in the High Ituri, Belgian Congo. INEAC, Serie Scientific, No. 66, 91 pp.

Sanchez, P. and J.G. Salinas. 1981. Low-input technology for managing Oxisols and Ultisols in tropical Americas. Advances in Agronomy 34:279-406.

Sanchez, P. 1976. Properties and Management of Soils in the Tropics. Wiley, New York. 618 pp.

Soil Survey Staff. 1960. Soil Survey Manual. U.S. Department of Agriculture, Soil Conservation Service.

Soil Survey Staff. 1975. Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. U.S. Department of Agriculture, Agric. Handbook No. 436: 754 pp.

Soil Survey Staff, 1994. Keys to Soil Taxonomy. USDA Natural Resources Conservation Service. Publ. US Govt. Print. Office, 6th. Edition, 306 pp.

Smith, G.D. 1963. Objectives and basic assumptions of the new classification system. Soil Sci. 96:6-16.

Smith, G.D. 1965. Lectures on Soil Classification. Special Bull. No. 4. Pedological Society, Ghent, Belgium.

Sys, C. et al. 1961. La Cartographie des Sols au Congo. Ses principes et ses methods. Publ. INEAC, Serie Technique No. 66, 144 pp. Bruxelles, Belge.

Sys, C. 1968. Suggestions for the classification of tropical soils with lateritic materials in the American Classification. Pedologie, 18:189-198.

Tavernier, R. and C. Sys. 1965. Classification of the soils of the Republic of Congo. Pedologie, 91-136.

Tavernier, R. and H. Eswaran. 1972. Basic concepts of weathering and soil genesis in the humid tropics. 2nd. ASEAN Soils Confeence, Jakarta, 1:383-392.

Thorp, J., and G.D. Smith. 1949. Higher categories of soil classification: Order, Suborder, and Great Soil Groups. Soil Sci. 67:117-126.

Tsuji, G.Y., R.T. Watanabe, and W.S. Saki. 1975. Influence of soil microstructure on water characteristics of selected Hawaiian soils. Soil Sci. Amer. Proc. 39:28-33.

Uehara, G. and J. Keng. 1975. Management implications of soil mineralogy in Latin America. In: E. Bornemizsa and A. Alvarado (Ed.), Soil Management in Tropical America. North Carolina State Univ., Raleigh, N.C., 351-363.

Uehara, G. and G.P. Gillman. 1980. Charge characteristics of soils with variable and permanent charge minerals. Soil Sci. Soc. Amer. J. I, 44:250-252, II, 44:252-255.

Van Raij, B. and B.M. Peech. 197?. Electrochemical properties of some Oxisols and Alfisols of the tropics. Soil Sci. Soc. Amer. Proc. 36:587-593.

Van Wambeke, A. 1974. Management Properties of Ferralsols. Soils Bull., 23. FAO, Rome, 129 pp.

Van Wambeke, A. 1981, 1982, 1985. Calculated soil moisture and temperature regimes of South America, Africa, and Asia. Soil Management Support Services (SMSS) Tech. Monograph No. 2, 3, and 9. Washington D.C.

Wambeke, A. Van. 1992. Soils of the tropics: properties and appraisal. McGraw-Hill, New York. 343 pp.

Webb, P. 1995. A time of plenty, a world of need: The role of food aid in 2020. Published as "2020 Vision Briefs" by the International Food Policy Research Institute, Washington D.C. 2020 Brief 10, 2 pp.

Webster, R. 1968. Fundamental objections to the 7th. Approximation. J. Soil Sci. 19:354-366.

Wolf, J.M. and M. Drosdoff. 1976. Soil water studies on Oxisols and Ultisols of Puerto Rico., II. Moisture retention and availability. J. Agric. Univ. P.R., 60:383-394.

World Bank, 1993. World Development Report 1993. Investment in Health. Washington D.C.