Chapter 6

Soil Physical Properties

Fig. 6.1 Runoff and erosion during an intense rainstorm on an Andisol (Ustand) near Arusha, Tanzania. Photo courtesy of Markus Walsh

Soil physical properties are those responsible for the transport of water, solutes, air and heat in the soil. The main physical soil properties are depth, temperature, texture, structure, bulk density and water-holding capacity. The main processes involved are infiltration, tillage, compaction, percolation, leaching, runoff and erosion (Fig. 6.1). The critical take-home message of the first edition was that there is a difference in water tensions in clayey Oxisols and other *Ci* soils (Chapter 5) as compared to soils with high-activity clays. This difference is due to strong granular structure of

these oxidic soils, which makes them behave like sands at low soil moisture tensions (when wet), but more like the clays at high soil moisture tensions (when dry).

Several major issues have emerged since. These include the importance of the fine-sand and silt fractions in surface sealing and soil compaction, soil erosion at the landscape scale and conservation agriculture. Another recent concept is that of core soil properties, texture, mineralogy and soil organic matter (SOM), which are those that underlie ecosystem services (Palm *et al.* 2007). These properties do control most physical soil processes.

6.1 Depth of Rooting

The most obvious physical limitation – insufficient soil depth for adequate root development – is often ignored. Physical barriers to root development are probably less common in the tropics than in the temperate region because of the generally deeper subsoils of highly weathered soils, particularly in Oxisols, Ultisols and Alfisols, but they do exist. Soils having the *R* substrata type (lithic or paralithic contact at 50 cm or less) cover 98 million hectares, or 2 percent of the tropics (Chapter 5). A classic study at the International Rice Research Institute (IRRI 1964) showed that rice yields increased linearly as the effective depth of rooting increased from 10 to 40 cm.

Stone lines are found in many tropical soils, reflecting geological discontinuities (Ruhe 1959). When they occur at less than 50 cm depth, they are included in the *R* substrata type (Chapter 5). Aluminum-toxic subsoils are more common barriers to root development than shallow soils in the tropics; they cover about 1.4 billion hectares or 28 percent of the tropics.

6.2 Soil Temperature

Soil temperature is seldom considered a serious limiting factor in the tropics. As mentioned in Chapter 1, soil temperatures approximate air temperatures at about 50 cm depth, and are usually adequate for most tropical crops. There are two instances, however, in which soil temperatures can be limiting. These are excessively high temperatures in certain sandy topsoils and low temperatures in the tropical highlands.

6.2.1 Controlling Excessively High Soil Temperatures

Large areas of West Africa are covered by Alfisols that have high sand and gravel content in the topsoil (see Fig 4.10 in Chapter 4). The thermal diffusivity of these horizons is much lower than that of clayey topsoils. Consequently, they can retain large quantities of heat, particularly when dry. Studies in Ibadan, Nigeria, have shown that temperatures in such soils can reach 42 °C at 5 cm depth and 38 °C at 10 cm depth, when bare or recently planted (Lal 1975). When topsoil temperatures reach 35–38 °C, they inhibit the emergence of yam sprouts and virtually stop the growth of maize and soybean seedlings (Lal
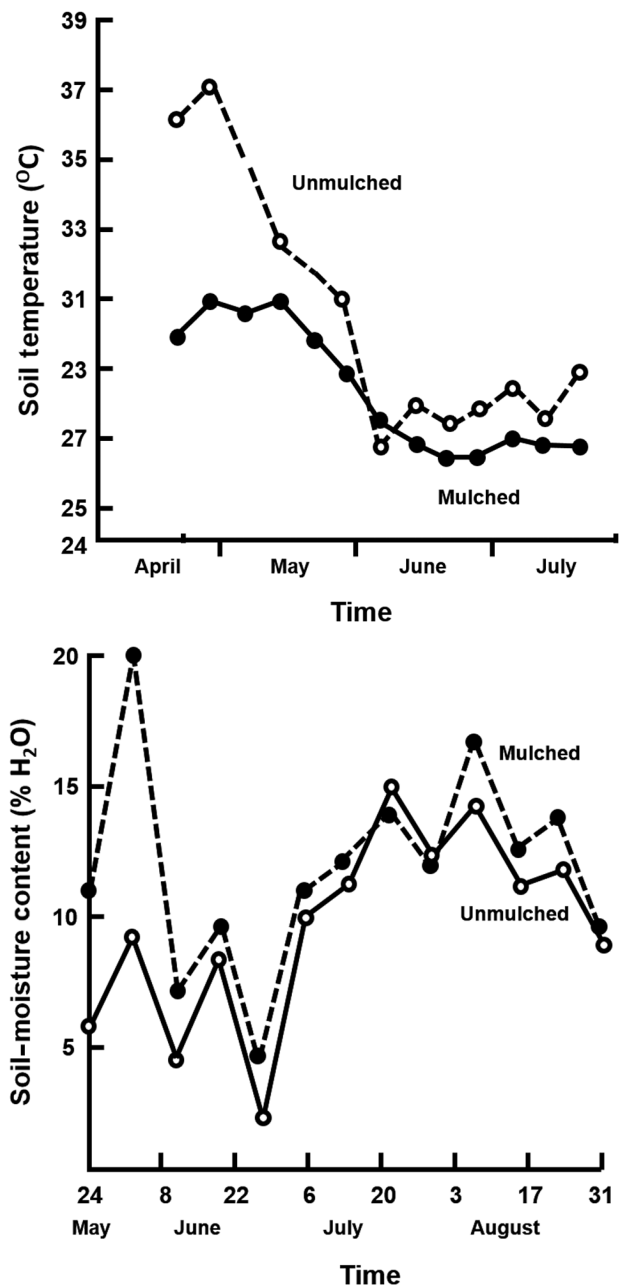

Fig. 6.2 Mulching decreases high soil temperatures and increases soil moisture in a loamy, gravelly Alfisol of Ibadan, Nigeria (Lal 1974). With permission from *Plant and Soil*

1974). Furthermore, Lal observed that nutrient and water uptake were severely affected at such temperatures.

The solution to this problem consists of mulching with residues from a previous crop. Mulching decreases soil temperatures down to 20 cm depth, as shown in Fig. 6.2. The unmulched plots had excessively high temperatures down

to that depth during early stages of growth. As crops develop a canopy soil temperatures decrease, but if a severe drought occurs later in the season, the mulch can prevent the return of excessively high temperatures (Lal 1974).

Mulching also increases soil moisture storage throughout the rainy season, as shown in Fig. 6.2. These increases in soil moisture are equivalent to about 8–12 percent of the rainfall received. In this example, the overall effect of mulching was to increase maize yields from 3.6 to 5.4 t/ha, and to decrease weed growth to one-third of that observed in the unmulched plots (Lal 1974). The practical problem is where to get biomass for mulching, but this can be addressed by conservation agriculture as discussed later in this chapter.

6.2.2 Controlling Low Soil Temperatures

In the tropical highlands, with isothermic or isomesic soil temperature regimes, many crops suffer from low-temperature limitations, particularly during wet periods. A wet soil also has low thermal diffusivity. Such is the case with certain pineapple plantations on Oxisols in the highlands of Hawaii. Low soil temperatures exert a negative influence on nutrient uptake, and consequently result in longer growth duration and lower yields (Ravoof *et al.* 1973).

The solution to this problem is also mulching, but with clear plastic. Unlike the straw mulch discussed before, clear-plastic mulch is a vapor barrier that increases soil temperatures through a greenhouse effect. Transparent polyethylene mulches have also increased mean soil temperatures and decreased irrigation requirements of potatoes in northern India, where low temperatures in the late fall season limit potato growth. Grewal and Singh (1974) observed that potato yields increased from 14 t/ha to 20 t/ha when such mulch was used. This increase was positively correlated with the rise in minimum soil temperatures caused by the clear mulch. They are commonly used in tropical highland regions in China for early planting, so that their fruits and vegetables reach the markets earlier when the prices are high. In addition to mitigating temperatures, plastic mulches also control weeds.

6.3 Soil Structure

Soil structure is the size, shape and arrangement of solids and voids, the continuity of voids and their capacity to retain and transmit fluids (Lal 1991). The main solid components are the primary mineral particles – sand, silt and clay (Fig. 6.3).

These primary particles plus SOM, iron and aluminum oxides, decomposing leaves and roots, and soil biota form aggregates. Water-stable aggregates give soils a good structure. They are generally grouped into two sizes. Macroaggregates ($>$ 250 μm), with macropores between them that are generally larger than 50 μm in diameter, drain gravimetric
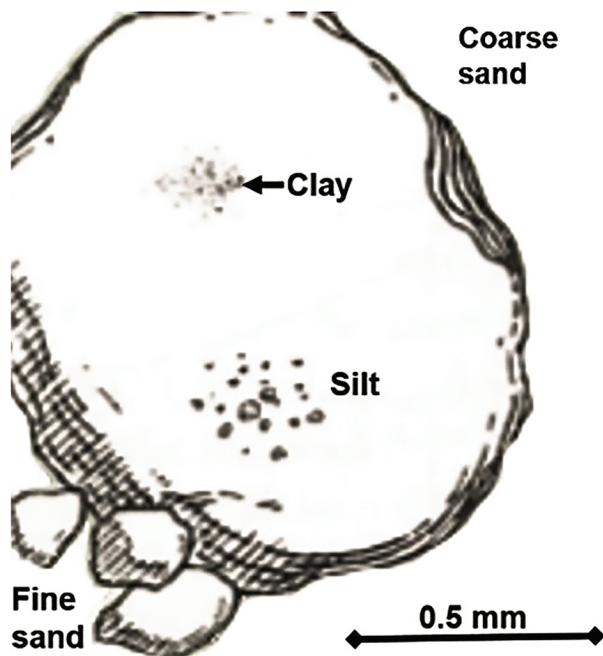
Fig. 6.3 Relative size of the primary soil particles. Coarse sand: 2.0–0.5 mm; medium sand: 0.5–0.25 mm; fine sand: 0.25–0.05 mm; silt: 0.05–0.002 mm; clay: $<$ 0.002 mm (2 μm)[1]. Source: Brady and Weil (2008). Adapted with permission from Ray Weil

water at −1 kPa to −10 kPa of soil moisture tension.[2] Microaggregates (50–250 μm) have micropores ranging from 0.2 μm to 50 μm in diameter that hold water at −10 kPa to − 1500 kPa of soil moisture tension. These micropores, therefore, hold most of the water available to plants.

Figure 6.4 shows a macroaggregate composed of sand, silt, clay, SOM, a decomposing plant root and voids (macropores). In variable-charge soils, such aggregates are frequently coated and cemented by iron and aluminum oxides. The figure also shows a microaggregate about 100 μm long that could have been part of the macroaggregate above.

6.3.1 Aggregate Formation

The processes involved in aggregate formation and destruction are shown in Fig. 6.5, divided among three processes for soils with permanent charge and a fourth process for soils with variable charge (Six *et al.* 1999, 2002b, c).

The first phase of aggregate formation is a biological one, starting with bacteria and fungi that begin to bind individual sand, silt and clay particles as well as pieces of plant- and root-derived organic matter (stage A). Afterwards, active root growth further binds particles by exudates and mycorrhizal

[1] One micron (μm) equals 10^{-6} m (one-millionth of a meter).
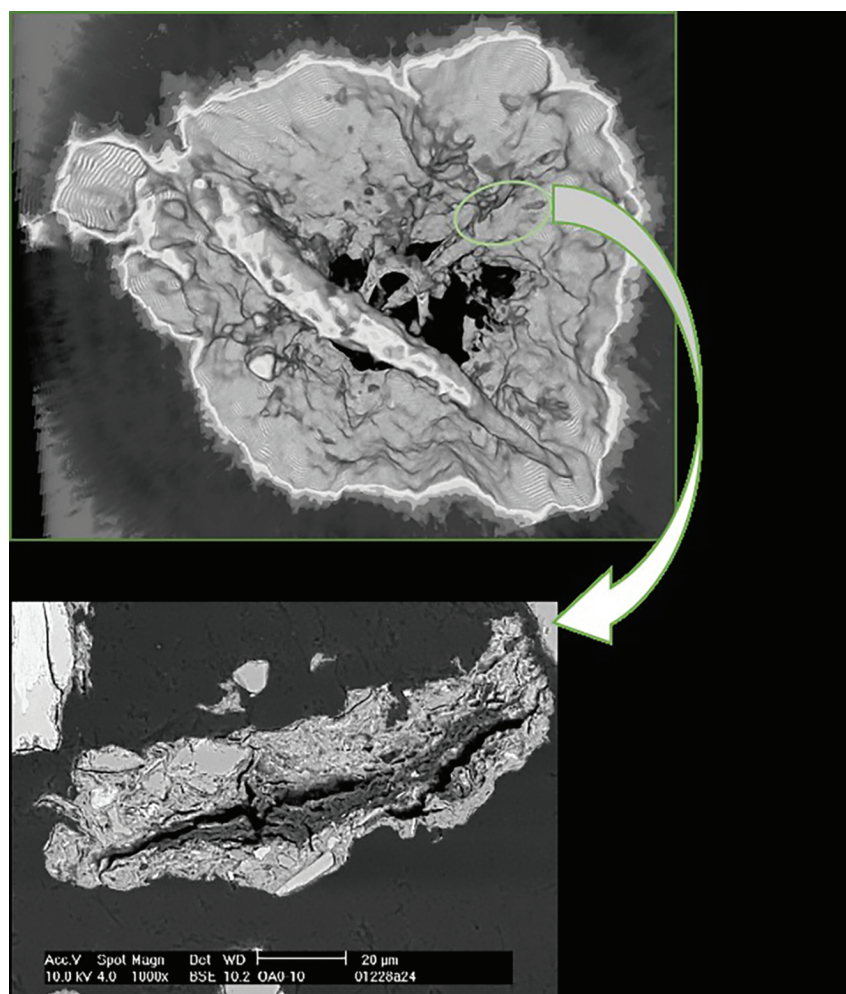
[2] 1 bar equals −100 kPa.

Fig. 6.4 Top: A macroaggregate (> 250 μm). Bottom: A microaggregate (about 100 μm long) that could have come from the macroaggregate above, as indicated by the arrow. Adapted from Pulleman *et al.* 2005. Source: Johan Six, Advanced Photon Microtomography, ETH-Zurich. With permission from Johan Six and *European Journal of Soil Science*

associations (stage B). Earthworm activity and other macro- and meso-fauna further contribute to the binding of primary particles and particulate plant-derived organic material into unstable macroaggregates (stage C). These three biological processes act simultaneously; their relative roles depend on the microbial population, type of plants, macro- and meso-faunal population and soil pH (see Chapter 10). Low soil pH promotes fungal activity over bacterial activity. In variable-charge soils a fourth process occurs – the binding of clay particles with iron and aluminum oxides (stage D).

The second phase of macroaggregate formation consists of the aging of the components, with further interactions between microbial activity, sand, silt and clay particles and organic materials (along with iron and aluminum oxides in the variable-charge soils). Wetting and drying cycles strengthen the macroaggregates, making them water-stable, and forming microaggregates inside them. Organic inputs are converted into slow and passive soil organic carbon (SOC) pools (Chapter 11). In calcareous soils (*b* soils in the Functional Capability Classification [FCC] system), which are permanent-charge soils, carbonate and bicarbonate precipitates help to strengthen aggregates in arid environments (Bronick and Lal 2005).

6.3.2 Aggregate Destruction

The principal aggregate destruction process is tillage, which can physically destroy macroaggregates, "pulverizing" the topsoil. A decrease in organic inputs to the soil also fosters aggregate destruction because it decreases microbial and macrofauna activity, weakening the bonds created by fungal hyphae, root exudates and mycorrhizae. Lack of plant cover also increases soil temperatures and stops the organic additions to the soil, weakening aggregates. In soils subject to

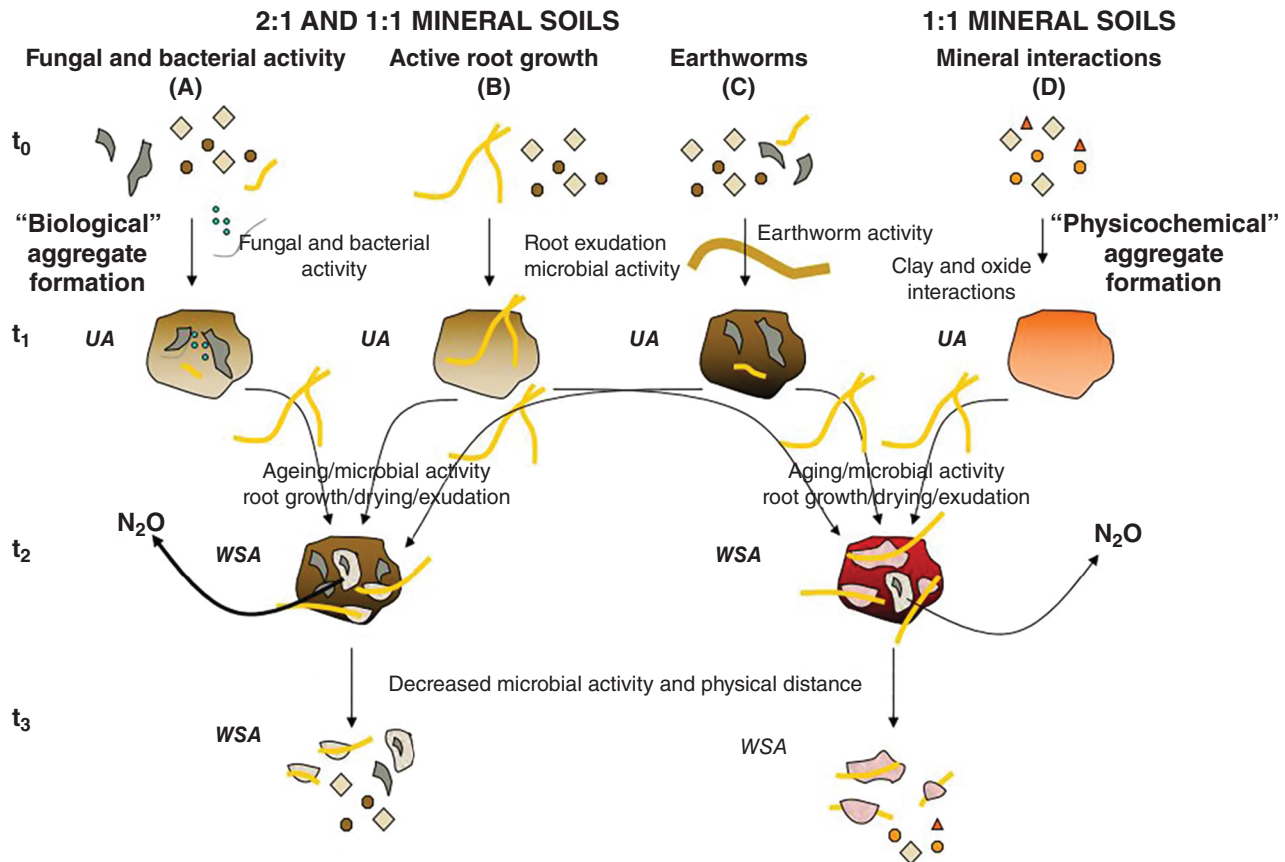# Soil structure – Soil biota – Carbon stabilization

Fig. 6.5 Aggregate formation and destruction. The processes are: (A) fungal and bacterial activity, (B) active root growth, (C) earthworm activity and (D) iron and aluminum oxide interactions in variable-charge soils. UA = unstable aggregate, WSA = water-stable aggregate. Adapted from Six *et al.* (2002a). With permission from Johan Six

sodification (*n* soils in the FCC system), large amounts of sodium (Na^+) ions can cause aggregate destruction by flocculation. The bottom of Fig. 6.5 shows the effects of the aggregate destruction processes.

6.3.3 Influence of the Three Core Factors

Texture, mineralogy and SOM determine soil aggregation. In sandy and loamy sand textures (< 15 percent clay), the primary particles tend to remain single-grained because the large macropores between them make microorganisms rapidly respire away organic inputs as carbon dioxide, instead of decomposing them slowly to form SOM that binds the primary particles into aggregates. It takes at least loamy (15–35 percent clay) and clayey textures (> 35 percent clay) to make aggregates. The choice of texture as the highest category of the FCC system (Chapter 5) indicates the importance of this core factor, not only in physical properties but in chemical and biological ones as well.

Clay minerals are also a determinant of the strength of aggregation in loamy and clayey textures. Soils with variable-charge clays (1:1 clay minerals, iron and aluminum oxides, *i* soils and allophane in volcanic soils (*x* soils in the FCC system) form tight bonds with primary particles and SOM, which give a strong structure to Oxisols and Andisols. A review by Six *et al.* (2002c) found higher aggregate stability in those soils than in soils with permanent charge dominated by 2:1 clay minerals.

SOM plays a major role in aggregation. It is an excellent binding agent with primary particles as well as with iron and aluminum oxides in variable-charge clay minerals. Soils dominated by such minerals show stronger aggregation at lower SOM levels than soils with permanent-charge minerals (Denef *et al.* 2002). Six *et al.* (2002c) found that a decrease in SOM contents results in a smaller decrease of aggregate stability in soils with variable-charge clays than in those with permanent-charge clays.

What is considered a good structure depends on the desired speed with which air and water move through the soil. A good structure for growing flooded rice is that attained by puddling (the destruction of aggregates), to eliminate downward water movement (Sanchez 1973). For other tropical systems, a good structure is one which maintains aggregate stability upon abrupt changes of soil moisture and intense rainfall (Pereira 1956).

Soil pores are where the action is in terms of air and water dynamics, as well as biological activity. While originally measured indirectly, it is now possible to quantify the soil pores directly, including pore connectivity and tortuosity, through non-destructive image analysis techniques (Moran and McBratney 1992). For example, Pires (2009) provided insights of the spatial arrangement of Oxisol pores in response to compaction.

6.3.4 Measuring Soil Structure

There is no single parameter that adequately measures soil structure, although water-stable aggregate stability is often used in the laboratory (Pereira 1956, Six *et al.* 2000a, b), and is qualitatively estimated in the SoilDoc field kit (Weil 2011). Pretreatment of soil, previous water content and differences in sand size distribution among soils can confound interpretation of these measurements.

Field tests using double-ring infiltrometers, when adequately replicated, are perhaps the most pragmatic means of evaluating soil structure, by estimating saturated hydraulic conductivity. Field infiltration measurements integrate many of the physical variables and provide a soil volume large enough to reduce the variability caused by insect and root channels. Lugo-López *et al.* (1968) applied this technique to 749 soils in Puerto Rico and found that infiltration rates during the first 3 hours depended on the initial soil moisture content. After the fourth hour, infiltration rates became constant and approximated the saturated hydraulic conductivity. A summary of their results by soil order appears in Table 6.1. The high maximum and minimum infiltration rates of Oxisols, Ultisols and Mollisols reflect their good structure, the very high maximum values in Alfisols and Inceptisols probably reflect sandy topsoil texture, and the low range of Vertisols indicates their high content of expanding 2:1 clays. It is important to note the wide range of infiltration rates within soil orders, which indicates that generalizing at the order level tells you only that Vertisols have lower infiltration rates than Oxisols, Ultisols and Mollisols.

6.3.5 Structure of Major Soils of the Tropics

Taking the idea of core soil properties (texture, mineralogy, SOM), I use examples from some of the most extensive tropical soils to describe the range in soil dynamics commonly found in the tropics.

Oxisols, and oxidic or rhodic groups and subgroups of Ultisols and Alfisols (Nitisols in the World Reference Base (WRB) system), generally possess excellent and strong granular structure. These are the *Ci* soils in the FCC system. Many

Table 6.1	Ranges in infiltration rates of Puerto Rican soils, grouped by soil orders (57 soil types and 749 tests). Measured after 4 hours, equivalent to their saturated hydraulic conductivity (Lugo-López *et al.* 1968).

| Soil order | Infiltration rate (cm per hour) | |
	Maximum	**Minimum**
Oxisols	12	8.4
Ultisols	11	7.4
Mollisols	13	8.2
Alfisols	32	2.7
Inceptisols	33	2.7
Entisols	7	2.3
Vertisols	7	0.1

Oxisols can be plowed a day after heavy rain with little aggregate disruption.

The excellent structure of *Ci* soils is caused by primary particles aggregated into very stable, sand-sized macroaggregates (shown in brown in Table 6.2). Their stability is due to their high clay content and coatings of amorphous iron oxides. Soil-organic-matter content is also correlated with aggregate stability in Oxisols, as it plays a cementing role between clay particles. When estimating soil texture by hand, clayey Oxisols initially feel like sandy loams. As one continues to work the moistened soil with one's fingers, it gradually feels more clayey as the macroaggregates are progressively destroyed.

When Oxisols are subjected to particle size analysis without pretreatment with sodium dithionate to remove free iron oxides, the clay contents read lower than when iron oxides are removed. In an example given by Moura and Buol (1972), the clay content of a Eutrustox increased from 40 percent to 83 percent when iron oxides were removed. The actual clay content of such Oxisols can be estimated by multiplying the water content at −1500 kPa by a factor of 2.5 (Soil Survey Staff 1970). This is a classic pedotransfer function.

The above generalizations apply to other soils carrying the *Ci* designation, mainly oxidic and rhodic groups and subgroups of Alfisols (Nitisols), including well-known ones like *Terra Roxa Estruturada* in Brazil and Kikuyu Red Loam in Kenya.

These generalizations do not hold throughout the Oxisol order. Uehara *et al.* (1962) observed different structural characteristics in Oxisols of similar clay contents, and mineralogical composition (primarily kaolinite and amorphous iron and aluminum oxides). Differences in aggregate stability could not be correlated with free iron oxide contents beyond the 5 percent level. Cagauan and Uehara (1965) then determined that these differences were associated with the degree of anisotropy (clay orientation) inside the aggregates. A more oriented system of

kaolinite particles cemented or coated with iron oxides provides stronger aggregates than a less oriented arrangement. The greatest degree of anisotropy has been found in ustic soil moisture regimes.

Oxisols in udic regimes exhibit less clay orientation, as is found in the well-researched *Latossolo Amarelo, textura muito pesada* (Yellow Latosol, very heavy texture, Acrudox),

with over 80 percent clay throughout the profile, and which covers extensive areas of the Brazilian humid tropics, north of the Amazon River, and the Congo rainforest in southern Cameroon. They do not show granular structure (Chauvel *et al.* 1991). Soils in continuously humid climates do not retain as strong a structure as those with marked seasonal moisture fluctuations (Denef *et al.* 2002).

Table 6.2   Thin sections of soils with contrasting physical properties. Thin sections from Eswaran and Drees (2002) and Stanley Buol (personal communication, 2016).
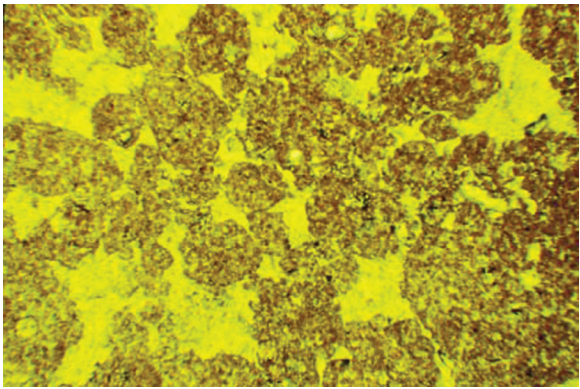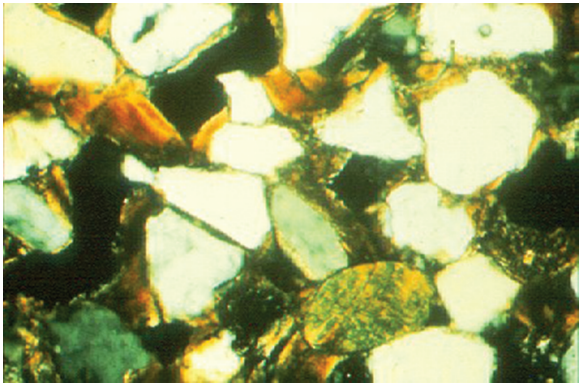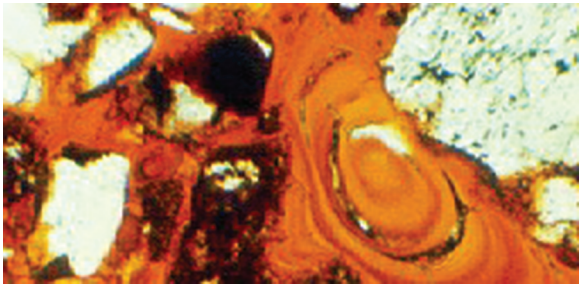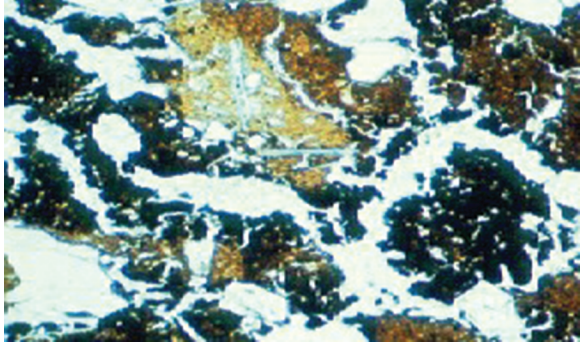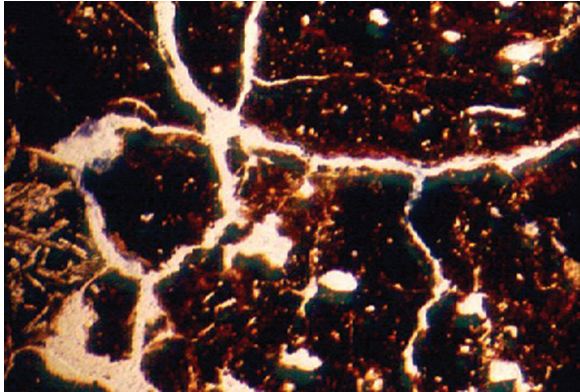
Soils	Micro-morphology	Texture	Clay mineralogy	SOM
Oxisol, from Stanley Buol (Typic Haplorthox, clayey, kaolinitic, isothermic). FCC = *Ciakq*.				
	Sand-sized macroaggregates (brown), with micropores inside; macropores in yellow	Clayey, > 35 percent clay	Kaolinitic with iron and aluminum oxide coats; variable charge	High
Alfisols/Ultisols, from Eswaran and Drees (2002). Thin sections from Ult. FCC = *SC* type.				
	Sandy horizon, where clays have moved to the subsoil. Mostly quartz sand grains, with some silt particles and organic matter. Large pores in black.	Sandy, < 15 percent clay	Siliceous; permanent charge	Low
	Argillic horizon, showing clay skins	Probably clayey, > 35 percent clay	Kaolinitic with iron and aluminum oxides; variable charge	Low

Table 6.2 | *(cont.)*

Soils	Micro-morphology	Texture	Clay mineralogy	SOM
Andisol, from Eswaran and Drees (2002). Probably a Udand. Probable FCC = *Lx*.				
	Dark colors are aggregates of allophane and imogolite; volcanic glass fragments in yellow (Note: large size of macropores (white))	Being amorphous, Andisols such as this have no real texture; considered loamy	Amorphous; variable charge	High
Vertisol, from Eswaran and Drees (2002). Probably an Ustert. Probable FCC = *Cdvb*.				
	Dark areas are smectitic clays, while macropores (white) are the product of shrinking and swelling	Clayey	Smectitic. Permanent charge	Low

Consequently, clay and SOM content, free iron oxides and the orientation of kaolinite within the aggregates are the main factors associated with the excellent structure of Oxisols, but the degree of manifestation of this structure varies.

Ultisols and **Alfisols** have less desirable structural properties because of a generally sandier texture in the A horizon. Clay skins, formed by clay migration from the A horizon, coat aggregates in the argillic B horizon. They are anisotropic and provide increased aggregate stability in the subsoil. Briones and Veracion (1965), working with Philippine "red" soils (Alfisols and Ultisols), found that the aggregate stability of these soils increased linearly with clay content up to about 50 percent clay. This is shown in Fig. 6.6.

The coarser-textured topsoils of Ultisols and Alfisols have lower aggregate stability than Oxisols, partly due to the differences between the sandy or loamy topsoils and the loamy or clayey argillic horizons, shown in the thin sections of Table 6.2. Alfisols with gravelly topsoils or with shallow subsoil depths are common in West Africa and parts of southern Africa (Kayombo and Lal 1993). These gravelly horizons have poor structure, low water-holding capacity

and excessively high soil temperatures, which can have a negative effect on root development and crop yield (Lal 1975). Soils with more than 10 percent gravel (2–25 cm in diameter) in the top 50 cm cover 145 million hectares or 3 percent of the tropics (Chapter 5).

Structurally inert soils (not shown in Table 6.2) have topsoils low in SOM, but with sufficient fine-sand and silt content (about 10–20 percent) that can bind larger sand and gravel particles, and behave very differently from other Alfisols. They are widespread in semiarid regions of the Sahel, southern Africa and Australia and are termed structurally inert by Lal (1986). These soils are treated separately from the more conventional sandy Alfisols and Ultisols of the humid and subhumid tropics, and are identified as *z* soils in the FCC system (Chapter 5).

Andisols also have extremely stable soil structure. The *x* attribute in the FCC system identifies such soils. The high SOM content of Andisols is intimately associated with allophane and imogolite, the main amorphous mineral species, providing strong aggregation. The macroaggregates in Andisols are somewhat larger than those in Oxisols, but

Aggregate size range	Oxisol (*Terra Roxa Legítima*)		Ultisol (*Massapé*)	
	Forest	Cultivated	Pasture	Cultivated
(μm)	Water-stable aggregates (%)			
> 2000	84.2	48.2	80.8	36.0
2000–210	2.1	41.3	15.3	30.2
< 210	13.7	10.5	3.9	33.8

Table 6.3 Effect of cultivation in an Oxisol and Ultisol from Brazil on wet-sieved aggregate size distribution without pretreatment. Adapted from Grohmann (1960).
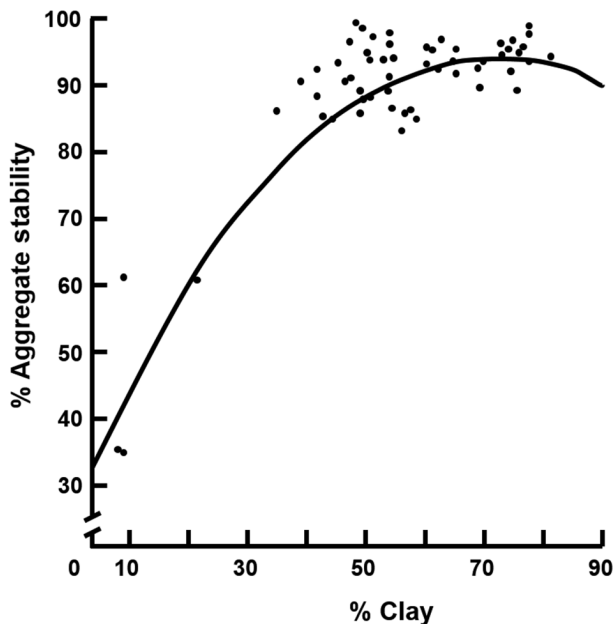

Fig. 6.6 Aggregate stability increases with clay content in "red" soils (Alfisols, Ultisols) in Luzon, Philippines (Briones and Veracion 1965).

their stability is similar. A study of 18 volcanic soils from Pasto, Colombia showed that 81 percent of the water-stable aggregates were greater than 2000 μm in diameter – very large macroaggregates (Escobar *et al.* 1972).

Andisols usually have very low bulk density (0.4 to 0.8 t/m^3) because of their mineralogy, high SOM content and high porosity (see thin section in Table 6.2). The absence or near absence of layered silicate minerals in many of these soils makes them difficult to disperse because of the strong bonding between allophane and organic matter. Attempts to estimate clay content by multiplying the −1500 kPa water content by 2.5 failed in these Andisols.

A few volcanic soils are essentially devoid of crystalline materials, such as the Hydrudands of Hawaii. They have thixotropic properties: upon force, the soil suddenly

becomes fluid (Swindale 1964). In most Andisols, however, thixotropy does not occur.

The structural properties of other tropical soils, dominated by permanent-charge clays – Vertisols, Mollisols, Aridisols – are different from those observed in most of the previously mentioned soils and more typical of temperate-region soils. In such soils, increased anisotropy means lower aggregate stability, because little or no iron coats are present.

Vertisols and vertic subgroups (*v* soils in the FCC system) have poor aggregate stability, which is associated with low soil-organic-matter content and expanding, smectitic clays (Lugo-López and Juarez 1959, Lugo-López and Pérez-Escolar 1969). Vertisols can be tilled adequately at a much narrower moisture range than other soils. When they are dry, shrinkage and cracking breaks the topsoil into massive clods of such strength as to make most tillage practices difficult (see thin section in Table 6.2). When wet, they are soft and sticky. One can certainly feel differences in clay mineralogy by driving on unpaved roads of "red" kaolinitic soils (Alfisols, Oxisols) and on "black cotton soils" (Vertisols) in Africa, often getting stuck in the Vertisols.

Aridisols have a notoriously weak structure. Because of their low SOM content and predominantly 2:1 mineralogy, aggregates easily fall apart when wetted. Those high in sodium saturation (*n* soils in the FCC system) disperse readily. Free carbonates and bicarbonates of calcareous soils (*b* soils) bind soil aggregates less strongly than SOM and iron and aluminum oxides.

In contrast, **Mollisols** have a good structure due to their high SOM content in both the A and B horizons.

The physical behavior of **Entisols** and **Inceptisols** cannot be generalized at the order level.

6.3.6 Changes with Tillage

Soil structure often changes with tillage. The degree of structural change varies with the core soil properties (texture, mineralogy, SOM), and with management.

The effects of intense cultivation on the size distribution of water-stable aggregates were determined by Grohmann (1960) in an Oxisol and an Ultisol from Brazil. The results in Table 6.3 indicate that cultivation reduced

Table 6.4	Fifteen years of conventionally tilled cropping decreased infiltration and macroporosity, but not microporosity, in a Eutrustox of Minas Gerais, Brazil (Moura and Buol 1972).	
Soil property	**Recently cleared**	**Annual cropping for 15 years**
Infiltration rate (cm/h)	82	12
A horizon:		
Percentage of macropores (> 50 µm)	25	11
Percentage of micropores (< 50 µm)	33	32
Percentage of water-dispersible clay	13	7
B horizon:		
Percentage of macropores (> 50 µm)	34	13
Percentage of micropores (< 50 µm)	30	33
Percentage of water-dispersible clay	1	7

Table 6.5	Pressures exerted by different soil compacting agents	
Agent (weight)	**Pressure exerted (kPa)**	**Reference**
Animals:		
Human (70 kg)	557	Alegre and Cassel (1996)
Goat/sheep (42 kg)	278	Cumming and Cumming (2003)
Cattle (300 kg)	353	Cumming and Cumming (2003)
Wildebeest (180 kg)	568	Cumming and Cumming (2003)
Elephant (2.2 t)	223	Cumming and Cumming (2003)
Machinery:		
Small tractor	49	Alegre and Cassel (1999)
Zero-tillage planter	157	Alegre and Cassel (1999)
Wheeled vehicle (4–10 t)	200–400	Soane (1986)
Tracked vehicle (4–10 t)	25–40	Soane (1986)
Bulldozer (20 t)	376	Alegre and Cassel (1996)

the percentage of macroaggregates larger than 2000 µm by about half in both soils, which were converted into smaller macroaggregates (210–2000 µm). But the percentage of microaggregates (< 210 µm in this example) did not increase in the Oxisol, while it increased drastically in the Ultisol, with a less strong structure. These microaggregates can clog the macropores between the larger aggregates and decrease infiltration.

Moura and Buol (1972) compared the effects of 15 years of annual cropping in a Eutrustox and observed that infiltration rates decreased from 82 cm/h to 12 cm/h (Table 6.4). The decrease in infiltration was due to a sharp decrease in macropores (> 50 µm) in both the A and B horizons, whereas the micropores (< 50 µm) remained essentially unchanged. Compaction by machinery was the cause of the decreased macroporosity. Moura and Buol also observed that water-dispersible clay contents decreased in the A horizon with cultivation but increased in the B horizon. Some clay translocation took place and this reduced macroporosity. The observed drop in infiltration rate, however, could be considered beneficial because of reduced percolation and potential leaching.

One aspect that is seldom considered is that mineral fertilizer applications, when properly managed, generally improve soil aggregation, in comparison to unfertilized soils (Subbian et al. 2000, Hamza and Anderson 2005). When crops are well nourished, they have higher root volume, protect the soil from erosion with their crop canopy, and provide more fresh organic inputs and then SOM through root decomposition and incorporation of crop residues.

6.4 Soil Compaction

Soil compaction is the increase in bulk density expressed in tons of soil per cubic meter and the accompanying decrease in pore space, resulting from the application of pressure to the soil by farm machinery, livestock trampling, raindrop impact and other means in sufficient amounts to overcome soil strength. The force applied per unit area varies as shown in Table 6.5 and is not directly a function of the weight of the compacting agent. Human feet and cattle hooves exert more pressure than many machines, which is why there can be severe soil compaction along cattle trails between tussock-type grasses, and particularly around watering points. The same occurs with wild antelopes, which exert more force than the much larger elephants, because of their

thin hooves in comparison with the much broader elephant feet. Bulldozers exert less force than wheeled tractors, because their weight is distributed along the tracks. Zero-tillage planters, because of their weight, often exert greater force on the soil while injecting seed and fertilizer in slits than tractors pulling conventional planters.

Soil strength (load-bearing capacity) involves the soil's resistance to cohesive and frictional forces. Cohesive forces break the bonds between soil particles, while frictional forces make soil particles slide over each other (McKenzie *et al.* 2002). Soil strength is highest when soils are dry, and rapidly decreases with increasing soil moisture content. Soil strength also depends on the three core soil properties. The strongest soils are clayey, with kaolinitic–oxidic mineralogy, and high in SOM. Soil strength is usually measured as resistance to cone penetrometers (Alegre *et al.* 1986).

Cattle trampling around watering holes in semiarid areas is a major contributing factor to soil degradation. In his detailed study in a sandy–silty Entisol of Northeast Nigeria, Usman (1994) quantified that trampling increased bulk density and resistance to cone penetrometers, created a dense layer at 6–8 cm depth, decreased porosity from 32 percent to 16 percent and decreased infiltration by over 90 percent. In better-aggregated loamy Alfisols of southern Brazil, compaction by trampling was avoided because of the maintenance of a pasture cover over the soil (Silva *et al.* 2000).

In terms of the depth of soil affected, there are three main forms of soil compaction: surface sealing and crusting, hardsetting and plow-pan formation.

6.4.1 Surface Sealing and Crusting

Soil surface sealing or crusting is a major management problem that has received considerable attention in semi-arid West Africa (Fig. 6.7), southern Africa and Australia. Surface sealing occurs when the soil is wet, while crusting refers to seals that have dried and hardened (Roth 1992). The sealed layer at the soil surface is about 5 mm thick (Fig. 6.8).

Fig. 6.7 Surface sealed sandy Alfisol in Burkina Faso.

Surface sealing is most acute in structurally inert Alfisols. Surface sealing does not occur in loamy sands and pure sands because these soils are single-grained – there is nothing to compact. It seldom occurs in Oxisols and Andisols because of their strong granular structure, nor in smectitic silty and clayey Aridisols and Vertisols. Again, the three core factors, texture, SOM and mineralogy, play a determinant role in this process.

Surface sealing prevents seedling emergence, sharply reduces infiltration, decreases water storage in the soil and triggers runoff, and hence erosion. Unlike other kinds of soil compaction, surface sealing is largely due to raindrop impact.

Valentin and Bresson (1992) recognized three types of crusts, structural, erosional and depositional, in the Sahel. They are formed in sequence. Structural crusts begin to develop during the first minutes after high-intensity rains hit a dry topsoil. Erosional crusts consist of an exposed silt–clay layer after the removal of sandy particles by wind or runoff. Depositional crusts are formed by translocation of clay particles and their subsequent deposition away from the original location.

Mineralogy plays a major role in defining crust formation. In topsoils with smectitic clay mineralogy, **structural crusts** mainly result from aggregate breakdown. They are caused by entrapped air compression when a dry soil is suddenly and thoroughly wetted. The advancing water compresses air in the soil pores until small air explosions occur, causing the breakdown of macroaggregates into primary particles (Yoder 1936). This process is called slaking, and occurs in aggregates that are not strongly bound by iron and aluminum oxides or by SOM.

Valentin and Bresson (1992) described a swelling crust, commonly observed in tilled arid loamy soils with smectitic clay mineralogy. Upon wetting, clay lattices expand and fill the interstices between cracks. This process can trigger runoff within a few minutes of rainfall. The swelling process then combines with the rapid slaking of aggregates, creating a crust. Upon drying, the crusts crack and curl. They are often photographed as the effects of global warming on increasing droughts, which is usually unrelated.

In the structurally inert Alfisols, structural crusts are made of a layer of loose sand and gravel-sized grains, overlaying a layer of finer material. They develop primarily as a result of raindrop impact, which forms microcraters, the walls of

Fig. 6.8 A thin, sealed layer of about 5 mm from the surface of a structurally inert sandy Alfisol of Segou, Mali.

which present a clear, vertical sorting of particles. A lack of smectitic mineralogy prevents slaking and swelling (Valentin and Bresson 1992). Such crusts are common in the Sahel.

Erosional crusts consist of one rigid, thin and smooth surface layer, rich in fine particles, a result of the destruction of structural crusts. Voids are generally restricted to some cracks and vesicles, and in arid environments they are often referred to as "desert pavement."

Depositional crusts are typically very compact. Separation between fine particles (plasma) and coarse particles (skeleton) induces alternate microbeds. Still, "depositional crusts" form in standing water and develop where surface flow is hindered. In puddles, the larger grains sink rapidly and form the bottom layer, whereas the finer grains deposit more slowly and form the top layer (Valentin and Bresson 1992).

The presence of algae and fungi strengthens both erosional and depositional crusts. Particularly under sclerophyllic (cactus-type) vegetation, they become hydrophobic or water-repellent (McKenzie *et al.* 2002).

Surface sealing has a devastating effect on the hydrology of the Sahel. It was amazing to see, at the beginning of the rainy season when the soils are surface-sealed, a 5-cm layer of water flowing on flat terrain and eventually emptying into the Niger River, with minimal infiltration (Fig. 6.9). Not only is rainfall marginal in the Sahel, but also much of it does not get inside the soil.

After some dry weather, farmers plow with cattle and break the crust, allowing water to infiltrate. In the meantime, much of the rains that were supposed to replenish moisture in the soil profile are lost. A feasible partial solution is live fences with leguminous shrubs such as *Ziziphus mauritiana*, and some *Acacia* species that can survive the 9-month dry season and prevent surface sealing by providing a leaf canopy under which the soil remains porous and runoff water infiltrates, replenishing some of the field subsoil moisture. In addition, these live fences attenuate wind and water erosion, fix nitrogen, produce high-value fruits, in the case of *Ziziphus*, and replace dead fences made from sorghum or millet stems (see Chapter 19).

Surface crusts can be reversed when vegetation and soil fauna recolonize crusted areas (McKenzie *et al.* 2002). Simply leaving twigs or straw on the soil attracts termites in the Sahel, where the resulting "biological tillage" breaks the surface seal (John Wendt, personal communication, 1980). But the need to use every bit of biomass for fuel and animal feed in semiarid areas prevents this from becoming a realistic intervention, at scale. Therefore, sealed surfaces have to be broken with tillage, be it biological tillage via termites or mechanical tillage by plowing. But they return after the next rain.

6.4.2 Hardsetting

Another form of soil compaction, unrelated to surface sealing or the application of force to the soil surface, is hardsetting. It occurs when much of the entire soil becomes so hard as it dries that it is virtually impossible to cultivate until it is rewetted (Mullins *et al.* 1992). Hardsetting in a cultivated soil usually involves destruction of soil aggregates during wetting, and an increase in bulk density and soil strength in subsequent drying. Hardsetting happens without the application of an external force, making this process a unique form of natural soil compaction.

Hardsetting occurs in soils with little or no water-stable aggregates, in textures ranging from loamy sands to clay loams, with kaolinitic or hydrous mica mineralogy and low SOM content. When thoroughly wetted, such soils lose their structure by the slaking process described previously, and a subsequent slumping of dispersed soil particles. As the soil dries, the whole profile hardens from the surface downwards, reaching extremely high bulk densities (1.8 t/m^3) and soil strength in the top meter (Mullins *et al.* 1992). Figure 6.10

Fig. 6.9 Runoff flowing on a level, surface-sealed Alfisol near Niamey, Niger.

Fig. 6.10 Trying to auger through a hardset, sandy Alfisol in Mali. Photo courtesy of Markus Walsh

shows how difficult it is to auger a hardset, sandy Alfisol during the dry season. When a hardset soil is wetted again by rainfall or irrigation, it loses soil strength and decreases its bulk density.

Hardsetting occurs in large areas of the semiarid tropics with ustic soil moisture regimes. Hardsetting occurs (again) in sandy soils with a high fine-sand and silt content, low SOM and kaolinitic clay mineralogy. It also occurs in Alfisols, Entisols and Inceptisols of the Sahel, Botswana and Australia (Nicou and Charreau 1980, Peltier 1993, McKenzie *et al.* 2002) in soils that have no water-stable aggregates. Hardsetting is common in "duplex" soils of Australia (Natraqualfs), where only the A horizon hardsets, aided by high sodium saturation (*n* soils in the FCC system). Hardsetting does not happen when smectitic clays are present because they shrink and swell with changes in moisture. It also does not happen in coarse sands (Quartzipsamments) because they have no structure as such, nor in Oxisols, Andisols and Mollisols, which have mostly water-stable aggregates. Such soils and many Entisols and Inceptisols with water-stable aggregates remain friable when dry. Hardsetting does not happen in udic soil moisture regimes.

Management practices that minimize soil disturbance and add crop residues can prevent hardsetting. Mullins *et al.* (1987, 1992) report that some maize farmers near Kabwe, Zambia incorporate chopped cereal stalks into the topsoil, which prevents hardsetting. When there is a short rainy season in Botswana, farmers delay planting, having to wait until the first rains have sufficiently softened the soil, which can diminish yields (Willcocks 1981).

6.4.3 Plow Pans

Tillage and farm machinery traffic can also induce subsoil compaction in the form of a plow pan. The depth of the pan varies from 10 cm to 60 cm and is usually several centimeters thick. Plow pans can develop in most tropical soils except Vertisols, where shrinking and swelling through the profile prevents their formation.

Although Oxisols in subhumid savannas (Ustox) are the strongest-structured tropical soils, excessive tillage can produce plow pans that lead to classic land degradation symptoms. The Brazilian Cerrado was opened with heavy disk harrows, used to incorporate lime to a depth of at least 30 cm, as an effective way to eliminate aluminum toxicity and allow for crop root development to that depth (González-Erico *et al.* 1979). Due to the large farm size, the disk harrows used became larger, and after a few years a plow pan developed at a depth of 12–15 cm, where water-dispersible clays have moved to from the harrowed topsoil (Lopes and Daher 2008). They are locally called *pé de grade* (foot of the harrow). Movement of water-dispersible clays, a product of partial aggregate breakdown, helps form these plow pans.

Plow pans form at a depth of 15–20 cm in loamy and clayey Alfisols and Ultisols of the African savanna, and in semiarid regions with intensively mechanized cultivation, resulting in restricted infiltration and root penetration, and

lowered grain yields. The situation is worse with 25-cm-deep moldboard plowing (Kayombo and Lal 1993).

6.4.4 Managing Soil Compaction

Perhaps the best management practice with such soils, other than the appropriate tillage, is to prevent compaction, by protecting the soil surface with mulch or plant canopies that decrease the energy of raindrop impact and the rate of SOM decomposition as well. A bare soil is very exposed to surface compaction. Lal (1975) showed that mulching also prevented excessively high soil temperatures, increased soil water storage, decreased weed infestations and inhibited runoff and erosion in loamy textured Alfisols of Nigeria. Evidence from sandy textured Ultisols of the Amazon supports Lal's findings (Wade and Sanchez 1983). In traditional shifting cultivation systems, the soil is never tilled but it is protected with an ash mulch and, later, with a constant crop canopy.

Mulching can prevent surface sealing in most soils. In practice, the only practical mulch is the one that is produced *in situ* by leaving crop residues on the soil surface. Transporting mulch from outside the fields is expensive, in capital or labor, and only feasible for very small areas, growing high-value crops. Leaving the land fallow so that some grass and tree seedlings establish helps to break crusts down. Valentin *et al.* (2004) found that physical properties were restored after a fallow period of 10 years on a clayey loam soil in Cote d'Ivoire, whilst crusts persist over a longer time on sandy soils.

Consequently, management to minimize or prevent the different kinds of soil compaction varies with the core soil properties. As mentioned previously, sands (Quartzipsamments) have no aggregation and therefore are not subject to compaction. At the opposite end of the soil spectrum, Vertisols with cracking and swelling smectitic clays do require conventional tillage and this must be done during a relatively narrow range of moisture content. Soils that are highly susceptible to surface sealing or hardsetting require tillage every year. In most other soils, minimum or no tillage is feasible and should be the preferred option, both in easily compacted soils as well as the most highly aggregated soils, Oxisols and Andisols. Kondo and Dias Júnior (1999) showed that resistance to compaction increased with increasing clay content in Oxisols. Many loamy Oxisols suffer readily from compaction (by definition, there are no sandy Oxisols).

6.5 Soil Water

6.5.1 Soil Water Retention

Soil water (soil moisture) is divided into three classes according to its potential energy, or soil moisture tension, which is now expressed in negative kilopascals (kPa) and previously in bars (1 bar equals −100 kPa). A saturated soil has zero tension (0 kPa). The first class, **gravitational water**, is that which is held in the macropores, normally between 0 kPa and −10 to −30 kPa. This tension range is called the
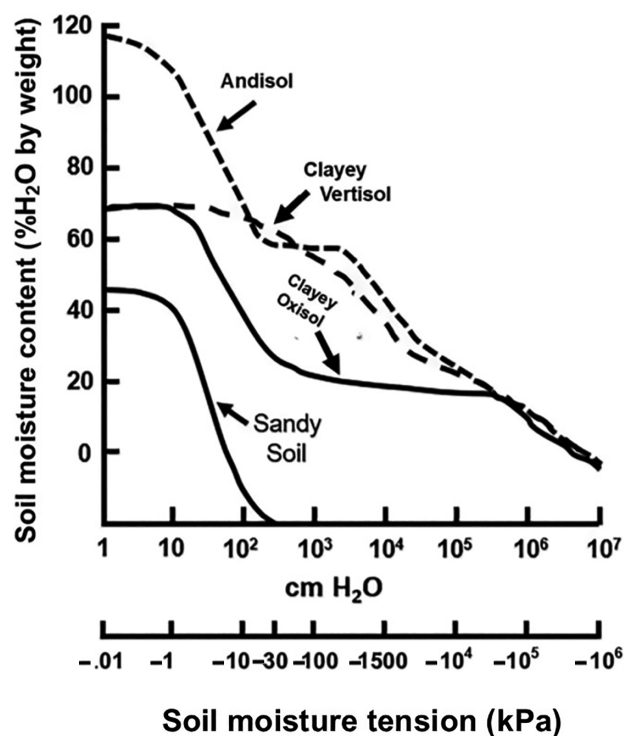
Fig. 6.11 Moisture-retention curves of a sandy soil, a clayey Oxisol, a clayey Vertisol and an Andisol.

Fig. 6.12 Soil-moisture retention curves of different aggregate fractions of an Oxisol (Sharma and Uehara 1968).

"field capacity," defined as the range at which the downward movement of water ceases. Secondly, the **available water** to plants resides mainly in the micropores, as films, where most of the nutrient uptake and ion exchange reactions take place. In soil chemistry, we call these films the soil solution. Soil moisture tension increases as the soil dries and the films become thinner. The available water is that which is held between the field capacity and the permanent wilting point (−1500 kPa). **Residual water**, the third class, is held at tensions lower than −1500 kPa, but it is not relevant to plants (McKenzie *et al.* 2002). However, some gravitational water is also available to crops, so the term "available water" is often an underestimate.

The differences in structure between broad kinds of tropical soils result in dramatic differences in their water-retention properties. Figure 6.11 shows the classic soil moisture characteristic curve of a sandy soil and two clayey soils, one with oxidic and the other with smectitic mineralogy, and an Andisol with amorphous mineralogy. The sandy soil empties its pores of gravitational water at tensions close to −10 kPa, while the smectitic clay does this at −50 kPa. This is what is traditionally known as field capacity, but the tensions vary from the classic 0 to −30 kPa definition.

The moisture-retention pattern of a clayey, well-aggregated Oxisol is a hybrid of these two (Fig. 6.11). These Oxisols hold as much water as smectitic soils, up to
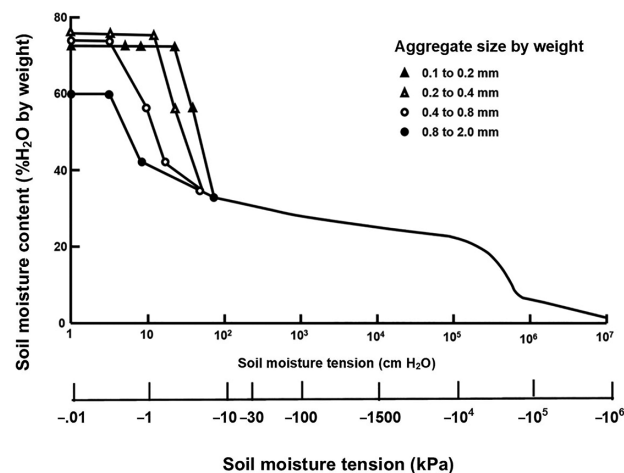
approximately −10 kPa, but drain their macropores at about that tension, thus reaching field capacity, as sands do. Oxisols act like sands at low tensions because of their strong, sand-sized macroaggregates, but hold water like smectitic soils at higher tensions. Therefore, they have a narrower available-water range than other clays. The most commonly accepted value for Oxisol field capacity is about −10 kPa (Ruiz *et al.* 2003).

Many Oxisols have drought problems that are completely out of proportion to their clay contents. The micropores in the microaggregates may be close to saturation, while the macropores between the aggregates are totally depleted of available moisture to crops. These unique properties are due to the aggregate size distribution. Figure 6.12 shows that the rapid drainage at soil moisture tensions between −1 kPa and −10 kPa is due to the predominance of sand-sized water-stable aggregates (2 mm) in these soils. At moisture tensions greater than −20 kPa, the aggregate size is irrelevant because it is the micropores within the aggregates that are being drained.

Andisols also possess unique water-retention characteristics. They hold considerably more water at lower tensions than other soils because of the high macroporosity and low bulk density of their aggregates. If the water content is calculated on a weight basis, the figures may range from 100 percent to 300 percent water. If calculated volumetrically (the correct way), their moisture contents may run as high as 84 percent water at −30 kPa field capacity and 45 percent water at the wilting point, −1500 kPa. Andisols, therefore, hold more water at a given tension than most other soils, as shown in Fig. 6.11 Although the quick attainment of field capacity is due to the drainage of large pores between very stable microaggregates, the high microporosity inside these aggregates accounts for their particular water-holding capacity (Forsythe and Diaz-Romeu 1969, Swindale 1969).

Andisols generally have more water available to plants than Oxisols because organic matter–allophane microaggregates are more porous than kaolinite–iron oxide microaggregates.

Ultisols and Alfisols with oxide coatings on kaolinitic clays seem to have better moisture-retention properties than Oxisols in general. The large areas of tropical soils with conventional 1:1 and 2:1 layer-silicate mineralogy have moisture-retention curves similar to those presented in standard textbooks.

6.5.2 Water-Holding Capacity

The definition of available water as the difference in volumetric water (percent water by volume) held at field capacity (−30 kPa) and that at the permanent wilting point (−1500 kPa) is still widely used. The original work of Briggs and Shantz (1914), using one plant (sunflower) and one loamy soil, has become a general principle. There are important limitations to this principle, both conceptually and quantitatively. Available water is not uniformly available in soils; roots do not extract it uniformly, and the replenishment of water lost by transpiration in soil close to the roots may be slow enough to cause wilting in the presence of ample water. Rice plants may be observed with wilted leaves, growing in a flooded soil on hot sunny days. There are also rather large differences between crops and varieties in their ability to extract water at different soil moisture tensions.

A study with several Oxisols, Vertisols, Inceptisols and Entisols in Zambia, by Maclean and Yager (1972), showed that soil moisture tensions between −10 kPa and −20 kPa are better approximations of the actual field capacity than the classic value of −30 kPa. When the available water was calculated as the difference between −30 kPa and −1500 kPa, the result was an underestimation of the available-water range by 35 percent compared with actual field measurements in these soils.

Sharma and Uehara (1968) in Hawaii and Wolf (1975) in Puerto Rico have shown little difference in water content between −100 kPa and −1500 kPa. A series of *in situ* studies on Oxisols and Ultisols in Puerto Rico and Brazil led Wolf (1975) to recommend that the available-water range of these soils should be estimated as the difference in water content between −10 kPa and −1500 kPa. Brazilian scientists now consider the available water range in Oxisols to be that held between −6 kPa and −100 kPa (Resck *et al.* 2008), and the old −30 kPa to −1500 kPa field capacity to wilting point range is no longer applicable to these soils. The field capacity limit has also been lowered from −30 kPa to −10 kPa in Australia, where most soils are not Oxisols (McKenzie *et al.* 2002).

Table 6.6 shows some representative available-water ranges, albeit using the old soil moisture tension limits and expressed gravimetrically. Regardless of texture, the available-water range of Oxisols is low, less than 10 percent. Ultisols generally have higher available-water capacities, Andisols hold much more water, and the two permanent-charge soils (Aquept and Ustert) hold about twice the available soil water than Oxisols.

Access to available soil water by plant roots depends on how deep they can grow, and this also depends on

management. A 22-year experiment in a Cerrado Oxisol indicates that the available water stored in the top 100 cm ranged from 576 mm to 672 mm (Resck *et al.* 2008). Maize roots can reach this depth only after lime and gypsum applications that promote calcium leaching into the subsoil. Otherwise, they are limited to the water held in the topsoil (Chapter 9).

Available-water capacity is one of the most important soil properties. Pedotransfer functions have been developed to estimate this capacity using commonly measured physical properties. The functions that seem to fit best for the tropics are those that include texture, mineralogy and SOM. Gaiser *et al.* (2000) obtained better predictions when they subdivided soil samples from northeast Brazil and Niger according to whether they had low-activity clays ($<$ 24 cmol$_c$/kg clay) or permanently charged clays of smectitic and mixed mineralogical families. Pedotransfer functions for estimating volumetric available water capacity are based on a direct regression between the soil water content at field capacity minus the soil water content at the permanent wilting point as the dependent variable; and clay, silt and organic carbon as independent variables. Gaiser and co-workers found that pedotransfer functions for the low-activity clay soils differed considerably from those for the high-activity clay soils, with respect to the contribution of total organic carbon and silt content to the prediction of soil water content at field capacity and wilting point. The overall pedotransfer functions for volumetric available-water capacity (AWC) were:

For low-activity clay soils

$$AWC = 0.247\ SOC + 0.244\ Clay + 0.080\ Silt \qquad (6.1)$$

For high-activity clay soils

$$AWC = 0.093\ SOC + 0.254\ Clay + 0.185\ Silt \qquad (6.2)$$

Pedotransfer functions have also been developed for other Brazilian soils (Tomasella and Hodnett 1998, van den Berg *et al.* 1997) with higher clay contents than Gaiser's data set, which are more typical of clayey Oxisols. All pedotransfer functions have to be locally validated, but the message is that clay mineralogy, texture and SOC have to be considered.

Bulk density is also needed to convert the usual gravimetric water contents to volumetric ones, which is what roots really use. Since bulk density is seldom measured, it may have to be modeled using assumptions.

6.5.3 Leaching

Infiltration in excess of the soil's available water-holding capacity causes nutrient losses through leaching. Estimates of leaching losses from selected tropical locations are summarized in Table 6.7. The amounts vary considerably with annual rainfall, soil properties and crops grown.

The Colombian study in Table 6.7 was carried out in highly porous Andisols, high in weatherable minerals, and

Table 6.6	Gravimetric available water in some tropical soil profiles at traditional field capacity (–30 kPa) minus the permanent wilting point (–1500 kPa). Adapted from Matthew Drosdoff, Cornell University, unpublished; Wolf and Drosdoff (1974); and Wolf (1975).				
Soil, texture and location	**Horizons**	**Percent clay**	**Percent H$_2$O (gravimetric)**		
	(cm)		**At –30 kPa**	**At –1500 kPa**	**Available**
Ustox; loamy; São Paulo, Brazil	0–23	13	10.4	4.6	5.8
	23–62	14	10.0	4.7	5.3
	62–120	15	10.8	4.9	5.9
Ustox; clayey; São Paulo, Brazil	0–14	47	27.6	17.7	9.9
	14–41	54	26.4	19.2	7.2
	41–80	56	28.4	20.0	8.4
	80–120	54	29.0	20.8	8.2
Ustox; very clayey; Minas Gerais, Brazil	5–15	71	27.7	23.5	4.2
	20–30	72	27.9	24.8	3.1
	40–50	68	26.3	24.7	1.6
	60–70	70	26.6	24.7	1.9
	70–80	60	28.1	25.0	3.1
Udox; very clayey; Puerto Rico	0–15	77	41.8	31.9	9.9
	15–33	77	40.3	33.6	6.7
	33–51	84	43.7	35.7	8.0
	51–86	83	42.1	34.2	7.9
	86–117	70	35.1	30.0	5.1
Humult; clayey; Puerto Rico	0–10	64	47.5	32.1	15.4
	10–23	69	39.8	31.4	8.4
	23–38	63	39.0	31.4	7.6
	38–64	48	63.7	30.1	6.6
	64–81	39	40.7	28.6	12.1
	81–114	33	39.6	28.0	11.6
Udand; "loamy"; Hawaii	0–5	——	47.1	29.9	17.2
	5–12	——	41.5	29.1	12.4
	12–20	——	46.1	32.8	13.3
	20–90	——	61.4	48.3	13.1
	90–100	——	77.4	59.2	18.2
Aquept; clayey; Philippines	0–20	61	48.5	29.9	18.3
	20–37	57	58.9	34.2	24.6
	37–58	50	47.0	36.3	20.7

(cont.)

Table 6.6 *(cont.)*

Soil, texture and location	Horizons	Percent clay	Percent H$_2$O (gravimetric)		
	(cm)		At –30 kPa	At –1500 kPa	Available
Ustert; Clayey; Puerto Rico	0–18	52	32.4	20.4	12.0
	18–36	55	40.6	23.5	17.1
	36–58	62	40.8	27.1	13.7
	58–86	63	38.6	26.2	12.4

Table 6.7 Magnitude of leaching losses in different tropical soils, data from lysimeters. From Suárez de Castro and Rodriguez (1955, 1958) for Colombia, Charreau (1972) for Côte d'Ivoire and Senegal and Reyes *et al.* (1961) for the Philippines.

Soil, location	Cover	Rainfall	Leaching	Nutrients leached (kg/ha per year)					
		(mm per year)		N	P	K	Ca	Mg	S
Udand, Colombia	Bare	2530	1771	249	0.23	202	776	232	–
	Pasture		1450	204	0.21	163	878	251	–
Aqualf, Philippines	Rice flooded, not puddled	2000	1248	11	0.13	60	391	313	89
			312	2	0.03	16	78	91	8
Ustalf, Senegal	Cropped	660	118	6	0.13	8	31	12	7
Udult, Côte d'Ivoire	Rubber	1569	845	79	2.90	63	31	40	–
	Banana	2040	828	235	1.20	24	256	113	–

under high annual rainfall, which produced high losses of nitrates, potassium, calcium and magnesium from leaching (Suárez de Castro and Rodríguez 1955, 1958). The data from the Philippines was obtained on an older soil, grown with flooded, but not puddled, rice, at two controlled leaching rates (Reyes *et al.* 1961). The low nitrogen values reflect the absence of nitrates under reduced conditions. The differences between the two controlled leaching rates suggests a similar composition of the leachate.

The three West African sites representing older Alfisols and Ultisols were obtained with *in situ* lysimeters (Charreau 1972). They show progressively higher nutrient losses with increasing annual rainfall. The high leaching losses of nitrogen and potassium in the Côte d'Ivoire soil are probably due to the fertilization of the banana plantation, as compared with the rubber plantation, which was not fertilized.

6.5.4 Runoff

When high-intensity rainfall events exceed the infiltration capacity of soils, or when some soils become surface-sealed, rains often cause considerable runoff (water running over the soil), even on gentle slopes. Table 6.8 shows the average values for annual runoff in four West African locations under forest, cultivation and bare soil conditions. Soil cover is the predominant factor affecting runoff, in spite of differences in slope and annual rainfall. The lower runoff values in cultivated soils than in bare soils underscores the need to keep a constant soil cover.

In a well-aggregated Andisol from Chinchiná, Colombia, considerable runoff amounting to 62 percent of the annual rainfall was measured by Suárez de Castro and Rodríguez (1955, 1958) on bare soils with slopes of 22 percent. Table 6.9 shows that large quantities of calcium and magnesium were washed away in the process. When pastures or coffee plantations were established, runoff, erosion and leaching losses decreased drastically. Terracing reduces runoff in young coffee plantations, but an old and very steep coffee plantation without terraces produced the least runoff, probably because the coffee canopy was well developed.

Runoff losses from experimental high-intensity rainstorms were evaluated by Barnett *et al.* (1972) on steep Ultisols and Inceptisols in Puerto Rico. Substantially lower runoff and nutrient removal was observed in the Ultisols, which were better aggregated.

| Table 6.8 | Magnitudes of annual soil runoff in four West African sites (Charreau 1972). Soils are Ustalfs in the first three locations and Udults in Abidjan. |

Location	Slope (%)	Annual rainfall (mm)	Annual runoff as percent of annual rainfall		
			Forest	Cultivated	Bare soil
Ouagadougou, Burkina Faso	0.5	850	2.0	0.5	40–60
Sefa, Senegal	2.0	1300	1.0	2.0	40
Bouaké, Côte d'Ivoire	4.0	1200	0.3	4.0	15–30
Abidjan, Côte d'Ivoire	7.0	2100	0.1	7.0	38

| Table 6.9 | Effect of cropping systems and conservation practices on annual water runoff losses and nutrients lost in the runoff, on an Andisol in Chinchiná, Colombia. The 6-year average rainfall was 2775 mm (Suárez de Castro and Rodríguez 1955, 1958). |

System	Slope (%)	Annual runoff (mm)	Nutrients in runoff (kg/ha per year)				
			N	P	K	Ca	Mg
Bare soil, tilled monthly	22	1730	25	0.98	24	238	152
Pasture	22	513	7	0.15	6	25	26
Young coffee plantation	45	190	8	0.04	2	6	7
Young coffee plantation with terraces	45	410	4	0.14	4	8	9
Old coffee plantation without terraces	55	59	1	0.08	1	2	2

Runoff losses are often deposited in the same fields, resulting in no net losses of water or nutrients at the field scale, although important local effects are created. In other cases, runoff steals most of the rainfall from surface-sealed Alfisols in the Sahel, as previously mentioned.

6.6 Soil Erosion

Soil erosion often is the most visible evidence of land degradation, and is indeed a major problem in much of the tropics. Soil is eroded by wind and water, the latter being the most extensive. There are three main types of erosion by water: sheet, rill and gully.

Soil erosion by water (A) is a function of five factors: rainfall erosivity (R), soil erodibility (K), slope gradient and length (LS), soil cover (C) and structural protection such as terraces (P), as described in the Universal Soil Loss Equation or USLE (Wischmeier and Smith 1978):

$$A(\text{soil loss in t/ha per year}) = R \times K \times LS \times C \times P$$

(6.3)

The USLE has been modified many times (Rosswell 1993, Renard et al. 1997, Millward and Mersey 1999, Tran et al. 2001). The modifications have not considerably affected the conceptual nature of the equation. In any case, I have seen few published articles where the equation is actually used to determine erosion, which usually is done directly by several methods.

6.6.1 Rainfall Erosivity (R)

Erosivity is the potential ability of rain to cause erosion (Lal 1976). It is independent of total annual rainfall, its seasonal distribution and the properties of soils on which it falls. Rainfall erosivity is best measured as the product of the kinetic energy of the storm (in mega joules per hectare [MJ /ha]) times the 30-minute maximum intensity (in mm/h), which is the highest average rainfall intensity during a 30-minute period. This measure (the erosivity index, EI_{30}) is considered the best estimate of rainfall erosivity (Wischmeier et al. 1958, Lal 1976). Rainfall intensity is also used as a measure of rainfall erosivity, ignoring the more difficult to measure kinetic energy. For example, Emerson (1995) suggested that rainfall intensities of 25 mm/h are sufficient to start erosion in Australia.

Rainfall intensity is generally higher in the tropics than in temperate regions because higher air temperatures provide more energy. The exceptions are subtropical areas (~30° N), often affected by hurricanes or typhoons. Rainfall intensity in the tropics is often sustained at 150–200 mm/h for 10–15 minutes, with large drops having a median diameter of 2.5 mm (Kayombo and Lal 1993).

A range of rainfall erosivity indices is shown in Table 6.10 as a function of latitude. High erosivity indices, $EI_{30} > 7000$, occur in the tropics, with the exception of the highlands in the coffee zone of Colombia, and a site at sea level in Hawaii. Low EI_{30} values are found in São Paulo state in Brazil and in Germany. The United States shows variability of two orders

Table 6.10 | Rainfall erosivity indices are generally higher in the tropics, but are highly variable

Location	Region, latitude	EI_{30} (MJ. mm/ha per hour) – range or mean	Reference
Manaus, Brazil	Amazonia 3° S	7510–17 710	Roth (1992)
Pereira, Colombia	Andes 5° N	2599–4686	Hoyos (2005)
Douala, Cameroon	Sea level 5° N	7400	El-Swaify and Dangler (1982)
Jakarta, Indonesia	Sea level 6° S	8536	El-Swaify and Dangler (1982)
Planaltina, Brazil	Cerrado 15° S	5190–10 990	Roth (1992)
Hilo, Hawaii	22° N	2886	El-Swaify and Dangler (1982)
Campinas, SP, Brazil	25° S	2553	El-Swaify and Dangler (1982)
United States	22–48° N	900–10 000	Foster et al. (1982)
Germany	42–46° N	400–1400	Foster et al. (1982)

of magnitude, including very high levels found in rainstorms in the Midwest and other temperate regions.

The low rainfall intensities of Germany and much of Western Europe led European soil scientists, when confronted with tropical rainstorms, to assume a great difference between tropical and temperate regions in rainfall intensity. American scientists, more used to a wide range of rainstorm intensities in their temperate regions, were less ready to make such an assertion.

6.6.2 Soil Erodibility (K)

Erodibility is the quantitative index of inherent susceptibility of soil to erosion by water. It is measured by soil losses from Wischmeier plots, 22.2 m long, on a uniform 9 percent slope, under continuously bare soil (El-Swaify and Dangler 1982). Soil erodibility is then calculated as tons per hectare of soil loss divided by EI_{30}. This is known as the K value, relating soil loss per unit of rainfall erosivity.

Some examples in Table 6.11 show that soils dominated by low-activity clays and iron oxides (Oxisols, Ultisols) as well as allophane (Andisols) have generally lower erodibility than soils with high-activity clays (Aridisols, Mollisols, Vertisols). The high erodibility of loose marl deposits in Morocco is probably indicative of the extreme erosion that is found in similar deposits in Haiti.

Vertisols are particularly susceptible to gully erosion. Specific vertic properties, such as low hydraulic conductivity, slumping due to slickensides and subsurface piping through cracks, facilitate gully head formation (Deckers et al. 2001).

Although erodibility is largely determined by the soil, the underlying parent material can play a role. One of the worst-case scenarios I have seen is when Vertisols are underlain by loose unconsolidated lake sediments, such as in the Nyando Basin near Lake Victoria in Kenya. At the start of the rainy season, cracks in Vertisols allow highly erosive rains to penetrate these extremely erodible sediments, rapidly creating huge gullies.

6.6.3 Slope Length and Gradient (LS)

Topography has major effects on soil erosion. The LS factor refers to slope length and gradient. The worldwide availability of Shuttle Radar Topography Mission (SRTM) satellite data at 90-m resolution makes the assessment of these parameters straightforward, although higher resolutions are needed for flat areas. Examples of the dimensionless LS values are included in Table 6.12, showing the values increasing with slope as well as slope length.

6.6.4 Vegetative Cover (C)

As previously indicated, the principal cause of soil erosion is the lack of soil cover. In a comprehensive study in mountainous Andisols near Pereira, Colombia, Hoyos (2005) found that the cover management factor C was the preponderant one, overriding the effects of topography in steep lands. Examples of C factors in West Africa are shown in Table 6.13. Roose (1975) gave the bare soil a C value of 1, the ungrazed savanna 0.01, and the dense forest 0.001.

General estimates of the magnitude of erosion losses in West Africa, from the semiarid Sahel to the humid tropics (Charreau 1972), underline the importance of keeping a cover over the soil, as Table 6.14 shows.

6.6.5 Protective Structures (P)

Terraces and other protective structures and practices (represented by the P factor) can have major positive effects on erosion control. This is dealt with in the next section.

6.6.6 Measuring Soil Erosion

The USLE is the primary model used for large-area spatial risk assessment in the tropics. But this model often overestimates erosion losses due to the small size of the plots – about 22 m long and 3–5 m wide. These small plots can also underestimate erosion when the slope or other factors not present in plots are evident in the landscape (Fig. 6.13).

The USLE is an empirical model, developed to assess plot-scale soil loss, but not sediment detachment and transport

Table 6.11	Soil erodibility indices of different soils. Adapted from El-Swaify and Dangler 1982.			
Soil order	**Soil**	**Soil series**	**Location**	**K ([t/ha]/EI_{30})**
Andisols	Hydrudand	Hilo	Hawaii	0.07
	Eutrand	–	Hawaii	0.16
Oxisols	Haplorthox	Catalina	Puerto Rico	0.01
	Eutrustox	–	Hawaii	0.09
	Haplotorrox	–	Hawaii	0.14
	Eutrotorrox	Molokai	Hawaii	0.22
Ultisols	Kanhapludult	Cecil	Georgia, United States	0.23
Alfisols	Ustalf	Saria	Burkina Faso	0.25
	Dunkirk loam	Dunkirk	New York, United States	0.69
Mollisols	Udoll	Marshall silt loam	Iowa, United States	0.33
	Ustoll	Shelby loam	Missouri, United States	0.41
Vertisols	Udert	Austin clay	Texas, United States	0.30
	Ustert	Lualualei	Hawaii	0.29
Aridisol	Camborthid	–	Hawaii	0.36
Entisol	Loose marl	–	Morocco	0.50

Table 6.12	Values for *LS* factor (dimensionless) in USLE. Adapted from Wischmeier and Smith (1978).			
Slope		**Slope length (m)**		
(%)	**(degrees)**	**50**	**100**	**200**
2	1	0.2	0.3	0.4
6	3	0.9	1.2	1.7
10	6	1.8	2.5	3.5
20	11	5.2	7.5	10.0
30	17	10.0	15.0	20.0
50	27	23.0	36.0	45.0

Table 6.13	*C* factor values (dimensionless) for different management systems in West Africa. Adapted from Roose (1975).	
System		**C**
Bare soil		1
Dense forest		0.001
Ungrazed savanna		0.01
Overgrazed savanna		0.1
Maize, sorghum, millet		0.04–0.9
Intensive rice cultivation		0.1–0.2
Cotton, tobacco		0.5
Peanuts (depending on planting date)		0.4–0.8
Oil palm, rubber, coffee, cacao with ground cover		0.1–0.3

at the watershed scale. The USLE has rarely been validated using ground observations of soil degradation.

Cohen *et al.* (2005) evaluated the effectiveness of models to predict erosion in a small watershed of western Kenya using standard remote assessment methods based on interpolated spatial data layers. They found that diagnostic models based on geographic information systems produced validation accuracies of 78 percent, while the association between USLE-predicted and observed erosion was only 38 percent.

Many process models exist on how to put all this information together. Probably the most commonly used one is

Table 6.14	Magnitude of annual erosion losses in four West African localities (t/ha per year) using USLE plots. Adapted from Charreau (1972).				
Location	**Ecosystem**	**Rainfall**	**Soil erosion (t/ha per year)**		
		(mm/year)	**Forest**	**Cultivated**	**Bare soil**
Bambey, Senegal	Sahel	500	0.1	0.1–2.6	18–30
Ouagadougou, Burkina Faso	Savanna	800	0.1	0.6–8.0	10–20
Abidjan, Côte d'Ivoire	Humid tropics	1800	0.03	0.1–90	108–170

Fig. 6.13   These erosion plots in Indonesia ignore the topography of this catchment. Courtesy of Meine van Noordwijk

Table 6.15	Large differences between plot- and watershed-scale soil-erosion estimates in Mendolong Research Area, Sabah, Malaysia (Sidle *et al.* 2006). With permission from Forest Ecology and Management.	
Land-clearing treatments	**Soil erosion (t/ha per year)**	
	Wischmeier plots	**Catchment**
Tropical forest	0.038	0.16–0.22
Manual clearing, no burning	0.11	2.20
Manual felling, wood extracted by crawler tractor, burning and planting	0.20	3.90

the Erosion-Productivity Impact Calculator (EPIC), which goes beyond erosion and is often used for crop modeling (Williams and Renard 1985). The Water Erosion Prediction Project (WEPP) developed by the United States Department of Agriculture National Soil Erosion Research Laboratory (Flanagan and Nearing 1995) is being successfully applied in the tropics (Ella 2005), combining characteristics of small watersheds (2000–10 000 ha) with soil erosion processes.

Land degradation in many policy studies focuses only on soil erosion, which economists quantify in terms of the value of soil loss or the cost of soil conservation measures. To our shame, many economists use the USLE soil-loss data from the Wischmeier plots as representative of real conditions at the field, watershed and even national scales. Most soil scientists know very well that this methodology overestimates or sometimes underestimates erosion losses due to the small size of these plots. But what is eroded from one spot is most frequently deposited in another one in the same field, often leading to no losses at the field scale.

Stefano Pagiola (personal communication, 1990), a natural resource economist, showed how erosion data, when cited from paper to paper, becomes conventional knowledge. He showed in a presentation that soil erosion rates in El Salvador average 130 t/ha per year. He dug back in the literature and found the original study – in one region of the country where Wischmeier erosion plots in four sites produced soil losses ranging from 10 to 130 t/ha per year. Guess which one became conventional knowledge.

Soil erosion is better estimated at the watershed (or catchment) scale. The differences that can occur between plot and watershed scales are shown in Table 6.15, where both types of measurements were done in the same land-clearing study in Sabah, Malaysia. Sidle *et al.* (2006) found a 20-fold difference in erosion estimates between the two methods, the larger numbers at the watershed scale. In this case, the USLE underestimated soil erosion.

Perhaps the best example of how to measure erosion in the tropics was done by Lal (1986), using catchments ranging from 2.6 to 15 hectares, in a land-clearing experiment near Ibadan, Nigeria (Table 6.16), where the effects of land-clearing methods and tillage were studied.

This experiment is one of the largest and best-run in the tropics, using different catchments that were necessarily of different area due to topography. The data show how both runoff and erosion increase with more intense land-clearing methods.

| **Table 6.16** | **Catchment-scale data from an Alfisol in Ibadan, Nigeria, grown with maize. Data are annual averages for the first 3 years after clearing. Adapted from Lal (1986).** |

Land-clearing treatment	Catchment area (ha)	Runoff (mm per year)	Erosion (t/ha per year)
Forest	15	< 1	< 0.01
Traditional slash and burn	2.6	6.6	0.02
Manual clearing plus conventional tillage	3.2–4.1	79.7	4.8
Bulldozer with shear blade, no tillage	2.7–3.9	104.8	4.1
Tree pusher–root rake, no tillage	3.1–3.2	170.0	15.7
Tree pusher–root rake plus conventional tillage	2.9–4.0	330.6	24.3

| **Table 6.17** | **USLE plot data in 1972 at the same location as in Table 6.16, mean values of all slopes. Annual soil loss averages for the first two years (Calculated from Lal 1976).** |

Treatment	Erosion (t/ha per year)
Bare fallow	106.6
Maize–maize, tilled	11.2
Maize–cowpea, no tillage	2.0

These data contrast sharply with Lal's results from the USLE plots in the same soil, which he used a decade before (Lal 1976), and are shown in Table 6.17. The USLE plots overestimated erosion losses for the catchment at 11.2 t/ha per year, compared with 4.8 t/ha per year (Table 6.16), in treatments cleared manually, tilled conventionally and planted to maize. If the bare fallow soil is used to calculate the erodibility factor *K* in the Wischmeier plots, the result, 106.6 t/ha per year, is an order of magnitude higher than all erosion experienced in the catchment plots.

Fig. 6.14 Effects of a high-rainfall erosivity event on a crop production landscape in Rwanda. ICRAF file photo.

In spite of their limitations, the Wischmeier erosion plots permit comparisons among soils in different ecosystems and management systems, but as shown they can underestimate or overestimate the more realistic catchment-based data. Other estimates from many countries in the tropics, compiled by Lal (1986), are in the range of 4–3600 t/ha per year.

The relationship between soil erosion and crop yields is complex because there are many other factors involved. Figure 6.14 shows the effect of a high-intensity storm on a cultivated landscape; the crop cover was unable to prevent erosion. In addition, the question of how to predict crop losses is difficult. For sub-Saharan Africa, Lal (1995) estimated annual crop yield reductions of 6 percent (3.6 million tons of cereals) in 1989, and estimated an increase, to 15 percent, by 2020.

There are many assumptions in such estimates, but these numbers suggest that crop productivity losses due to soil erosion are not overwhelming, in comparison, let's say, with post-harvest losses during crop storage, which average 30 percent (Sanchez 2015).

When gully erosion is unchecked, it can lead to catastrophic circumstances where no cultivation is possible, such as in Fig. 6.15.

6.6.7 Civil Engineering Erosion

While traveling in the tropics one often sees catastrophic erosion along rural roads. Ziegler and Giambelluca (1997) found that saturated hydraulic conductivity on unpaved roads in Thailand was ten times lower than adjacent soils, therefore increasing runoff and erosion along roadsides. This "civil-engineering erosion" is often photographed as if it has been caused by cultivation, and decorates many publications about soil degradation.

6.7 Soil and Water Conservation Practices

There is no question that soil erosion and water conservation are major challenges in the tropics, but what is being done about it? Tropical farmers and researchers have provided many ingenious solutions, some of which are described below. The principles of soil conservation in the tropics are no different from those developed in the temperate region. The high intensity of some tropical rainstorms, and poverty, however, require some special adaptations.

Conservation practices are generally of two types – keeping a vegetative cover over the soil and providing protective barriers against erosion. Since barriers such as biological or mechanical terraces require major investments in labor to construct and maintain them, farmers are unlikely to adopt them unless they have secure land tenure.

What follows are several examples of successful soil conservation in the tropics. Additional ones are found in books by Monengat (1991) and Müller-Sämann and Restrepo (1997) for Latin America, and Craswell *et al*. (1985) and Coughland and Rose (1997) for Southeast Asia.

6.7.1 Small-Scale Structures in the Field

Many small-scale farmers in Africa till their land with hoes and without animal or mechanical power. In well-structured, gently sloping Oxisols and oxic Alfisols of western Kenya, this works relatively well (Fig. 6.16). In less-well-structured soils, such as loamy Alfisols in Malawi and most Alfisols in subhumid areas of both West and East Africa, most farmers make ridges and furrows on just about any slope, planting crops on top of the ridges (Fig. 6.17). Often they use tied ridges, earthen bunds that are constructed at right angles to the furrows, at intervals of 1–4 m, effectively making small, shallow ponds to allow more time for water to infiltrate (Pereira *et al*. 1967, Hulugalle *et al*. 1987).

In semiarid northern Ethiopia, farmers use trench bunds, about 1–2 m long, 50 cm wide and 30 cm deep, located where there is plenty of runoff (Fig. 6.18). These trench bunds allow water that would run off to slowly infiltrate into the soil; this is one of many ways to store water in the subsoil. Tied ridges increase soil moisture storage, which

Fig. 6.15   Gully erosion has made this field in Koraro, Ethiopia, impossible to cultivate.

Fig. 6.16   Hand hoeing in a clayey Oxisol in Sauri, Kenya, the only land preparation practice. Fields are usually separated by earthen *fanya juu* bunds (not shown).

Fig. 6.17   Ridge and furrow system during the rainy season in Mwandama, Malawi, in a loamy Alfisol. Ridges are rebuilt every year.

can help avert the short-term droughts that are common in rainfed systems. Figure 6.19 shows the increased water availability with tied ridges. Sorghum, maize and cotton yields increased by 26–45 percent in a 6-year trial in Zimbabwe (Nyamudeza *et al*. 1991, 2001).

Throughout the semiarid tropics, microcatchments are commonly used to capture surface runoff. *Zai* holes are shallow pits surrounded by a hemisphere of stones that form a small catchment (about 3–10 m in diameter) where a valuable tree is often planted (Fig. 6.20). There are many variations of these techniques. Trash lines of organic

Fig. 6.18 Trench bunds in Koraro, Ethiopia, in a sandy Inceptisol (Ustept).

materials are also commonly used to slow down runoff. The overall strategy of these practices is to hold water for a longer time (Kayombo and Lal 1993).

6.7.2 Contour Cultivation

Planting along contours, instead of up and down the slope, is usually a feasible and sound practice, but often a difficult one to introduce to farmers who are used to plowing up and down slopes. All over the tropics, farmers indicate that when they tried contour cultivation, intense rains broke the contours and erosion got worse.

Results from Kunming, China, provide valuable insights (Table 6.18). At a gentle slope of 6 percent there were no major differences in soil loss between contour or downslope cultivation, with losses lower than 1 t/ha per year. On a steep 20 percent slope, downslope tillage produced slightly higher soil loss. It was at the extreme 50 percent slope where downslope tillage produced more than twice the soil loss than contour tillage. The advantage of contour cultivation is more evident for steep slopes.

Contour cropping, an inexpensive and simple technology, was adopted and maintained in the Dominican Republic after the research demonstrations had stopped (Carrasco and Witter 1993), while in neighboring Haiti, downslope cultivation is still widespread on steep slopes, with devastating results.
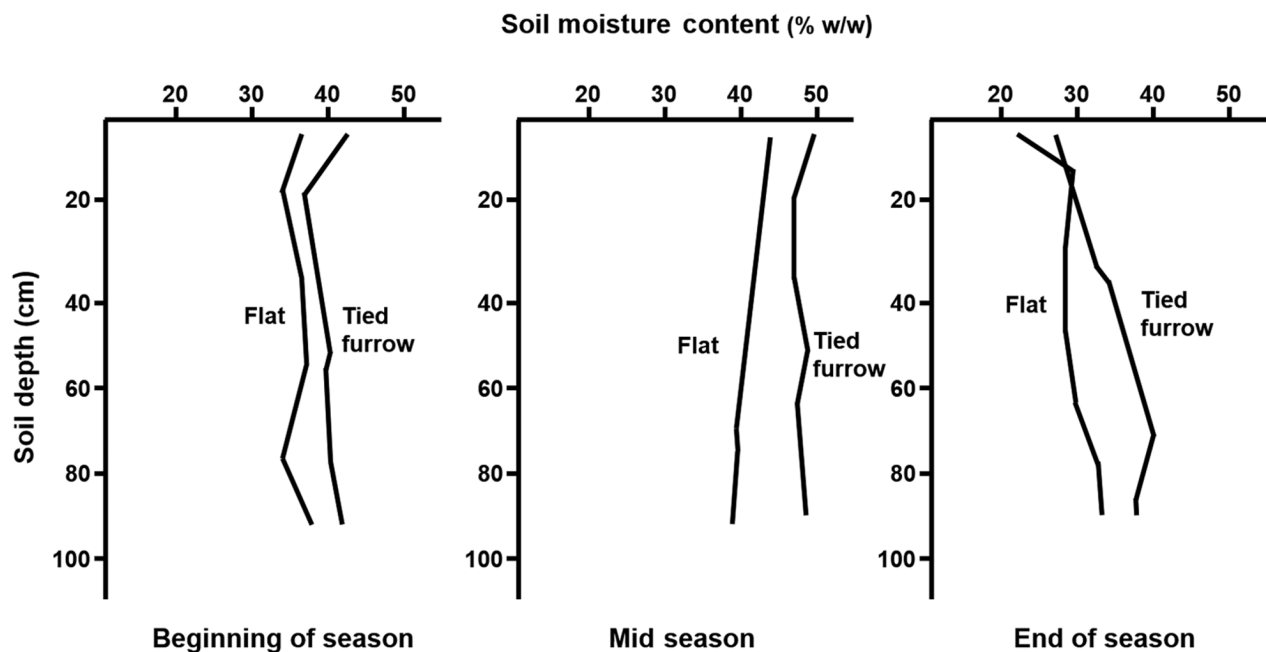

Soil moisture content (% w/w)

Fig. 6.19 The positive effects of tied ridges (tied furrows) on profile soil moisture in a Vertisol of Zimbabwe. Adapted from Nyamudeza *et al*. (1991)

Table 6.18	Annual soil loss (t/ha per year), average of 4 years under one crop of maize per year (1993–1996), conventionally tilled at Yunnan Agricultural University, Kunming, China, elevation 1930 m. Soil is probably an Ustult. Adapted from Fullen (2002).

Slope (%)	Soil erosion (t/ha per year)	
	Contour	Downslope
6	0.96	0.70
18	3.95	4.39
50	4.29	10.67

Fig. 6.20. *Zai* holes in Burkina Faso.

6.7.3 Contour Hedges

Planting trees or tropical grasses along contours provides effective barriers that protect the soil against erosion. Evidence of the positive impacts of these practices is well established (Roose 1970, Lal 1989, Young 1989, Juo *et al*. 1994, Kiepe and Rao 1994, Alegre and Rao 1996, van Roode 2000). Closely spaced trees on slopes reduce soil erosion by water, as they provide a physical barrier of stems, low branches, superficial roots and leaf litter, as well as allowing higher water infiltration due to better soil aggregation under the trees (Kiepe and Rao 1994). If leguminous, these hedges also fix nitrogen. Trees, however, do not deliver these functions until they are well established and have developed a litter layer, and they must be planted closely. Once established, most trees protect the soil indefinitely, provided they are well managed and the litter layer is not removed.

The perennial nature of tree and grass root systems provides a dependable source of carbon for microorganisms, which in turn promotes better soil structure and often higher macrofaunal activity, which in turn promotes higher porosity (Sanchez 1995). When contour hedges are composed of fodder trees (*Calliandra calothyrsus*, *Leucaena leucocephala*, for example) and grasses such as Napier or elephant grass (*Pennisetum purpureum*), they also provide livestock feed, without competing for area with crops. Vetiver grass (*Vetiveria zizanioides*), although capable of controlling erosion, is seldom used because it has no value as forage. Fruit or timber trees grown as an upper storey in such contours also provide additional income and ecosystem services (Garrity 1993, 1996; Garrity and Mercado 1994).

Njoroge and Rao (1994) developed a summary of multi-year trials across the tropics (Table 6.19). Under a variety of soils and slopes, contour hedges show their effectiveness in minimizing soil loss and runoff. It is important to space the contour hedges at least 4–5 m wide, to largely eliminate the competition with the crops in between, or else you begin encountering the limitations of alley cropping (Sanchez 1995; Chapter 19). The Malawi example, although effective in controlling erosion, resulted in low maize yields, partly due to competition between the crop and the trees, with only 0.9 m between hedges (Banda *et al*. 1994).

In semiarid climates, spacing between contours can be wider. Contour hedges in an essentially flat slope in Hyderabad, India, predictably did not have an erosion control effect. The effect is more pronounced with an increasing slope angle of up to 30 percent, with over 80 percent reduction in soil loss. At more pronounced slopes, this reduction in soil loss is less pronounced, at 40 percent for a 75 percent slope. For such steep slopes bench terraces may need to be constructed to adequately control soil erosion (Njoroge and Rao 1994).

Controlling soil erosion with planted hedges has an additional advantage, which is that the slope between the hedges becomes less steep and eventually flat in some instances, forming, in effect, bench terraces. These "biological terraces" are produced by taking advantage of the erosion process within the contour hedges, with the tree or grass growth keeping up with the higher soil surface at the lower end, something stone bench terraces cannot do. With

Location	Rainfall	Slope	Spacing between hedges	Duration of trial	Soil loss		Runoff	
					With hedges	Without hedges	With hedges	Without hedges
	(mm per year)	(%)	(m)	(years)	(t/ha per year)		(mm per year)	
Yurimaguas, Peru	2200	16	4	4.5	6	79	60	347
Citayan, Indonesia	2044	17	4	1	11	103	56	232
Los Baños, Philippines	2074	17	5	1	3	127	75	347
Ibadan, Nigeria	1358	7	4	6	< 1	5	72	252
Butare, Rwanda	1279	28	10	4	4	303	35	111
Ntcheu, Malawi	1125	44	0.9	6	2	44	—	—
Machakos, Kenya	750	14	4	4	< 1	19	4	21
Hyderabad, India	765	2	5.4	4	< 1	< 1	6	44

Table 6.19 Contour tree hedgerows dramatically reduce soil erosion losses and, to a lesser extent, runoff losses. Adapted from Njoroge and Rao (1994).

Fig. 6.21 Contour hedge terraces gradually become flat. Rwerere, Rwanda, ~2500 m elevation. Wheat is the crop and *Grevillea robusta* the tree, stunted at this high elevation. Drs. Erika Styger and Amadou Niang.

time, soil from the upper end of the terrace moves downslope and is captured by the lower hedge (Fig. 6.21).

Loss of topsoil from the upper third of these terraces can occur often with lower crop yields in relation to the more fertile lower end of the terrace where the topsoil accumulates (Garrity 1996, Walle and Sims 1999). One solution is to plant nitrogen-fixing tree fallows in the upper third of the terrace for 2 years, which, in the steep highlands of southwestern Uganda, added enough nutrients and SOM to even out the fertility gradient (Siriri and Raussen 2003). Furthermore, Agus *et al*. (1997) also found lower plant available water at the top of a terrace under alley cropping in Mindanao, Philippines, confirming the competition for water between closely spaced hedgerow species and the crop. That is one reason why alley cropping is not recommended (Sanchez 1995, Chapter 19).

6.7.4 Earth Terraces

During the colonial period in Africa, farmers were often forced to construct narrow bench terraces, a practice quickly done away with in many countries after independence, and not particularly effective. In its place, steep upslope terraces (*fanya juu* in Kiswahili, loosely meaning "throw upwards") are now widespread in East Africa.

Fanya juu terraces are mainly responsible for the environmental rehabilitation of Machakos District in Kenya (Tiffen *et al*. 1994). These terraces, constructed after consultation with villagers instead of being imposed on them, along with extension and credit programs, created the "more people, less erosion" paradigm. Tiffen and co-workers concluded that the Machakos District has sustained agricultural intensification and improved soil conservation and crop production for the last 40 years in spite of a population growth rate of 3 percent per annum. *Fanya juu* terraces have been found more effective in reducing soil loss and runoff than contour hedges in Machakos (van Roode 2000) because they present a solid barrier, unlike trees, at ground level.

The opposite strategy is to dig the furrows along the contour, but build the terrace downslope, and plant grasses. These are called raised bed terraces in Indonesia, where they have decreased soil erosion in steep slopes in Central Java from 106 t/ha to 34 t/ha per year (Adiningsih and

Fig. 6.22   Sagada rice terraces, Mountain Province, Philippines.

Fig. 6.23   A landscape in Tigray region, Ethiopia, with stone bunds along the contour.

Fig. 6.24   Stone mulch, Axum, Ethiopia. The two stones in the center were overturned before taking the photo.

Syarifuddin Karama 2004). However, the authors considered bench terraces made of stone to be more economically attractive in spite of higher labor costs.

6.7.5 Stone Bench Terraces

Indigenous tropical farmers have produced spectacular and long-lasting bench terraces made of local stones, which have controlled erosion for decades and centuries. The Inca civilization spread stone terraces called *andenes* (where the name Andes probably comes from), which are where their descendants grow tropical highland crops like potato, quinoa, wheat and barley, and raise cattle, llamas and alpacas. An iconic example is Machu Picchu in Peru. Gravity irrigation canals and drainage ditches, along with the terraces, showed excellent engineering by a culture that had not yet discovered the wheel. Many of these structures are now abandoned in many parts of the Andes, but many also retain their productivity.

Southeast Asia has similar examples in the Philippines (Fig. 6.22); Java, Sumatra, and Bali, Indonesia (Siebert and Belsky 1990); Sri Lanka; and other countries. Wetland rice is the main crop in these terraces, requiring soils to be flooded, which decreases soil strength and requires more maintenance. I have seen such stone terraces in West Sumatra that are wide enough to plant only two rows of rice, about 50 cm wide.

6.7.6 Stone Bunds

In semiarid highlands of the Tigray region of Ethiopia, most soils are stony Entisols and Inceptisols, and farmers have used stones to construct a plethora of soil and water conservation structures since the 1980s. A 30-year study by Nyssen *et al.* (2007) shows that sheet and rill erosion rates have decreased, while infiltration, spring discharge, vegetation cover and crop production have improved.

The first intervention is making stone bunds on the contour (Fig. 6.23). Rock fragments larger than 5 mm can cover as much as 57–85 percent of the surface soil in this region. By following the contour in slopes greater than 15 percent, the soil is displaced downslope, and in effect makes the slope flattened in about 8 years (Nyssen *et al.* 2000), like contour hedges and *fanya juu* terraces in other areas. Stone bunds have been shown to increase productivity in the semiarid Tigray region (~650 mm per year), but not in the humid Amhara region (~1980 mm per year), suggesting a soil moisture saving effect (Kassie *et al.* 2007).

Stones left on the fields have actually increased rainfall infiltration by protecting the soil from compaction by raindrop impact, and decreased surface sealing and crusting; they also reduce evaporation from the topsoil directly underneath the stones (Nyssen *et al.* 2001, 2002). These "stone mulches" save soil moisture and are shown in Fig. 6.24.

Halfway across the tropics, contour bunds made from duripan fragments in steep Andisols in Ecuador, when reinforced with grasses, were found superior to bench terraces or infiltration ditches in controlling erosion, requiring less labor and not as much loss of arable land (Dehn 1995).

6.7.7 Rehabilitating Eroded Landscapes by Community Action

Gully-ridden landscapes force farmers into extreme poverty, resulting in the classic "badlands" (shown above in Fig. 6.15). But when the community is mobilized and supported by science-based advice, the results can be remarkable. Community-based work during the past decade in the semiarid (500 mm annual rainfall) Koraro Millennium Village, in Hawzen Woreda in the Tigray region of Ethiopia, transformed much of an extremely degraded landscape, with stunted, extremely poor people, into a thriving community – also due to successful interventions in soil fertility, health, education, electricity and roads.

The area has a sharp sandstone escarpment to the south, which captures rains that reach the village as intermittent storm flows, causing gully erosion and reducing the arable land available. A comprehensive landscape rehabilitation plan was developed by a local agricultural engineer, Gigar Kebede, together with the community, supported by a government food for work program and the Millennium Villages Project (Chapter 2). Several technologies not only deviated a major gully from crop fields, but resulted in the village now having 43 hectares of irrigated land where there was none before. Some of these technologies are described in the following sections.

6.7.8 Controlling Gully Erosion

The restoration of gullied land involves larger-scale efforts. Figure 6.25 shows the construction of check dams, including the assembly of gabions (a cubic heavy wire mesh structure, filled with stones), the finished check dam and the captured sediments behind the dam that progressively fill the gullies. The gully bottoms are generally fertile and are often planted with palatable grasses and even tree legumes like *Sesbania sesban*. To that extent, it might be thought that the gully sides should also be planted, but often they are too steep.

6.7.9 Runoff Storage in the Subsoil

When cropland is next to hills or scarps, the potential for capturing runoff and storing it in the subsoil can be very significant. Percolation ponds are strategically located to capture runoff and allow it to percolate into the subsoil. Water stored in the subsoil is then retrieved downstream with shallow wells, and pumped to individual farmer fields (Fig. 6.26). Under these conditions, the subsoil is a great place to store water for subsequent irrigation.

Another way to capture water is via the ditches along roads, many of which are lined with cement in steep areas. It is simple to deviate the flow into storage ponds. Some of these ponds are underlain by strong polyethylene sheets or made with cement. Ethiopia now has hundreds of

Fig. 6.25 A stone check dam constructed with gabions in Koraro. Top left: gabions. Top right: construction. Bottom left: the finished dam, which is narrower because the gabions penetrate sideways into the gully wall. Runoff flows over the center of the dam. Bottom right: sediment is deposited behind the dam, which can be planted with useful trees like *Sesbania sesban* along the sides.

Fig. 6.26 Percolation pond (left) captures runoff from the scarp at Koraro. The water is allowed to percolate into the subsoil, and is pumped from shallow wells lower in the landscape where farmers have their fields (right).

thousands of these ponds, used for gravity or bucket irrigation (Nega and Kimeu 2002, RELMA 2005, Malesu *et al*. 2007).

6.8 Conservation Agriculture

Plowing to turn the soil over, control weeds and prepare a seedbed has been practiced since the dawn of agriculture in the Fertile Crescent (Hillel 2008). Except for traditional shifting cultivation, where a dibble or planting stick was the only tool inserted into the soil, virtually all other farming systems involve tilling the soil until a loose seedbed is obtained and weeds turned over. The planting stick gave way to the hand hoe or spade, and eventually to the animal-drawn plow. In other centers of origin for agriculture that did not have cattle or horses, such as Mesoamerica and West Africa, humans were the draft animals until large livestock were introduced. The *maresha* wooden plow, pulled by oxen, has been used for centuries in Ethiopia, probably not any different now from biblical times (Fig. 6.27). The wooden point was eventually replaced by iron plows.

Plowing changed radically and advanced enormously with Jethro Tull's invention of the moldboard plow in the eighteenth century, which inverted the topsoil, burying weeds in the process. Disk harrows, also an inversion tool, further destroyed clods and eventually produced a weed-free, soft seedbed. Mechanization of tillage operations in many tropical regions has gone much beyond the introduction of tractor-drawn moldboard plows and disk harrows. Excessive tillage often results in high losses of soil moisture, increases soil erodibility and compaction, and creates plow pans. The energy and carbon footprints are also high. Because of these excesses, a movement towards reducing tillage began in earnest during the middle of the twentieth century, particularly with the advent of modern herbicides.

Fig. 6.27 A farmer using an ox-drawn *maresha* plow with a wooden point, near Axum, Ethiopia. This practice dates back to 700 BC.

Conservation agriculture covers over 125 million hectares worldwide, with Brazil leading the tropics (Pittelkow *et al*. 2015). This is still only 9 percent of the total cultivated area of the world, but conservation agriculture occupies about one-third of the area cultivated to grain crops in Brazil (Six *et al*. 2002c). Derpsch (2008) estimates that the vast majority of areas under conservation agriculture (over 95 percent) are practiced in large, mechanized, well-fertilized commercial farms, with only about 450 000 hectares practiced in medium to small farms – roughly, those with less than 15 hectares of cropland. Conservation agriculture is known by a variety of terms: no-till, reduced tillage, minimum tillage, *plantio direto* (direct seeding) in Brazil, etc.

6.8.1 Principles of Conservation Agriculture

Conservation agriculture was based originally on four principles: (1) minimum or no mechanical soil disturbance; (2) crop residue returned to the soil, to cover the soil surface throughout the year; (3) weed control by herbicides; and (4) crop rotation. To this, Vanlauwe *et al.* (2014) added a very sensible but often forgotten fifth principle: (5) the appropriate use of fertilizer to enhance crop yields and crop residue production. All must be simultaneously undertaken.

Conservation agriculture, therefore, is an umbrella term that encompasses a range of cultural practices, based on these five components: Conservation agriculture is often equated to minimum or no tillage, ignoring the three other components, and causing confusion in the literature. The application of the five components is taken for granted in large-scale mechanized operations, but not so in smallholder farming situations, where residue return, herbicide application and even fertilizer use are not normal operations. For clarity, I will use the term no-till when only the first component is practiced.

Conservation agriculture represents a fundamental shift from the millennial paradigm: a clear seedbed with crop residues removed (Giller *et al.* 2009). Rather dogmatically, the FAO (2001) definition states, "as long as a farmer plows at least one crop during the rotation, he does not practice conservation agriculture." As we will see, occasional plowing is a requisite of some successful conservation agriculture practices in the tropics as well as in the temperate region.

The advantages and limitations of conservation agriculture have been debated not only in the scientific literature (Lal 1989, 1991, Six *et al.* 2002c, Giller *et al.* 2009, 2011, Palm *et al.* 2014, Powlson *et al.* 2014, Pittelkow *et al.* 2015) but in policy-oriented publications such as FAO (2001) and World Bank (2012), particularly as a tool to sequester carbon and mitigate climate change. In any analysis it is critical to know which of the five components of conservation agriculture are used.

Crop Yield Decrease

A meta-analysis of 5463 paired observations in 610 studies across 48 crops and 63 countries, including many in the tropics, by Pittelkow *et al.* (2015) provides an overall view of the effects on crop yields.

When only the no-till component was used, crop yields were 11 percent lower than with conventional agriculture, and this difference was maintained during the first 2 years and became larger when no-till was continuously applied for 10 years or more (Table 6.20). When no-till was combined with residue return, the conservation agriculture yield penalty was reduced to about 5 percent, and when the three components were applied, the difference was reduced to practically nothing. The use of herbicides, something new for many smallholder African farmers, was not evaluated in this meta-analysis.

Pittelkow *et al.* (2015) also found that the negative yield effects were present in ustic soil moisture regimes with only no-till, but became positive (+7 percent) when the three components were applied, probably due to improved soil water retention. They concluded that no-till alone decreases crop yields, but the difference with conventional agriculture is minimized when residues are returned and crops are rotated. In my view, crop residue return is the most critical component because it provides new carbon to the soil as well as year-round crop cover, while the effects of crop rotation are more often related to weed, pest and disease control.

Increases in SOC

SOC clearly increases in the top 10 cm of the soil after 5 to 10 years of continuous zero tillage, particularly if it is accompanied by crop residue return. This occurs because the organic inputs to the soil (residues plus crop roots) decompose to form additional SOC at a rate higher than the decomposition rate of SOC. The rate of SOC decomposition decreases in the absence of tillage. The overall increase in SOC was 325 ± 113 kg C/ha per year under no-till compared with conventional tillage in tropical and temperate regions (Six *et al.* 2002c), but not linearly with time. For Brazilian Oxisols, Sá *et al.* (2001) found that in continuous no-till with full crop residue retention, soil aggregation is rebuilt during the first 5 years, but topsoil SOC does not begin to increase until after that time. Table 6.21 shows this effect. Note that well-managed, conventional agriculture maintained SOC levels, but no-till increased it.

The increase in SOC results in higher biological activity, including that of macrofauna such as earthworms and termites as well as improved nutrient cycling.

Table 6.20	Results of the meta-analysis of paired comparisons between the application of various components of conservation tillage versus conventional tillage, which includes residue returns and crop rotation. Adapted from Pittelkow *et al.* (2015). Mean values and standard deviations (sd). I assume all fields used herbicides and were fertilized.

Comparisons relative to conventional agriculture (tilled with residues returned plus crop rotation)	Overall	1–2 years	10 years +
	Crop yield (%, mean $\pm$ sd) relative to conventional agriculture		
No-till only	-11 ± 5	-12 ± 5	-20 ± 8
No-till + residues returned	-6 ± 4	-5 ± 3	-5 ± 5
No-till + residues returned + crop rotation	-4 ± 2	-3 ± 2	-1 ± 3

Table 6.21	Changes in topsoil SOC in a Typic Hapludox of Paraná State in Brazil. Adapted from Sá *et al.* (2001).
System	**Change in SOC in top 40 cm (t/ha)**
No-till for 10 years	–4.8
No-till for 20 years	+17.4
No-till for 22 years	+18.9
Conventional tillage for 22 years	–0.1

Control of Runoff and Erosion

No-till and leaving crop residues partly on the soil surface dramatically decreases runoff and soil erosion. This is the clearest effect of conservation agriculture. Although the data vary, the review by Palm *et al.* (2014) indicates that runoff and erosion is reduced by one order of magnitude with conservation agriculture.

Better Water Provision

The large decrease in runoff and erosion losses means that additional water can be stored in the soil with conservation agriculture. Also, the higher SOC content improves soil structure (except in sands and loamy sands), resulting in higher infiltration rates due to more continuous macropores and higher soil moisture content, retained for longer periods. Improved soil structure facilitates earlier planting since the soil is softer and thus easier to plant by no-till.

Soil Compaction

Although plow pans are eventually eliminated by root and macrofauna, no-till planting equipment often compacts the topsoil due to its weight (Blanco-Canqui and Lal 2007). This is the reason why some farmers, although no-till advocates, do occasional deep tillage to ameliorate soil compaction.

Climate Regulation

The increase in topsoil SOC suggests that conservation tillage increases carbon sequestration and thus reduces carbon dioxide emissions to the atmosphere. Nowadays, carbon sequestration by conservation agriculture is considered one of the main pillars of climate-smart agriculture. The review by Palm *et al.* (2014) shows considerable variation in carbon sequestration in the top 40 cm due to differences among soils in texture, mineralogy, initial SOM content, the amount of crop residues added (a management variable) and crop-rotation schemes (another management variable). They recommend using the equivalent-soil-mass method and not the equivalent-soil-depth method that is normally used, as well as sampling the soils to at least 40 cm.

Using the equivalent-depth method in soils that have lower bulk density due to no-till may underestimate carbon sequestration under no-till, and sampling to 40 cm may overestimate carbon sequestration in no-till systems because depths of 20–40 cm usually show decreases in carbon content with no-till. Even with the appropriate methodologies, many conservation agriculture systems do not show increased carbon sequestration, while many others show decreases and a few show no change at all (Palm *et al.* 2014, Powlson *et al.* 2014). Therefore, it is not clear that conservation agriculture leads to increased carbon sequestration.

The addition of large quantities of crop residues often results in nitrogen immobilization for the first few years, and anaerobic conditions in the top few centimeters, necessitating additional nitrogen fertilizers to overcome this; but afterwards, mineralization of soil nitrogen exceeds the immobilization. The initial period may increase nitrous oxide emissions, but the available data do not clearly show the effects of conservation agriculture on nitrous oxide, and also methane emissions (Palm *et al.* 2014). Therefore, the climate regulation function of conservation agriculture should not be taken for granted. However, the elimination of tilling most of the soil surface saves time, labor and fuel (with lower carbon dioxide emissions from fossil fuels).

The core soil properties, namely texture, mineralogy and SOM, largely determine whether or not conversion from conventional tillage to conservation agriculture is advisable. The vast tropical literature and my own observations are summarized below.

6.8.2 Soils in Which Conservation Agriculture Works

Oxisols, Andisols, Nitisols, Oxic Groups of Ultisols and Alfisols (*Ci, Lx* Soils in the FCC system), on Gentle Slopes
These strongly aggregated soils are well suited for conservation agriculture. The Oxisol story in the Cerrado ustic savanna of Brazil illustrates this point. The Cerrado began its rapid and successful development in the 1970s. The first two decades focused on overcoming extreme acid soil infertility of the Oxisols, using disk plowing up to 30 cm depth to incorporate lime (González-Erico *et al.* 1979). Gradually, the soil structure began to deteriorate, plow pans often developed and SOC decreased, while erosion losses and runoff increased (Lopes and Daher 2008). The large farm size (~1000 ha) aggravated these problems, forcing quick land preparation, leaving the pulverized soil exposed to the first intensive rains of the single rainy season.

Conservation agriculture, using heavy seeding machinery and herbicides, began in earnest, increasing from essentially nothing in 1990 to 11.5 million hectares in 2005. No-till practices reduced soil erosion by 75 percent and runoff by 25 percent, while increasing crop yields (Lopes *et al.* 2004, Resck *et al.* 2006). A 21-year comparison of several crop rotations in a Typic Hapludox of southern Brazil showed that no-till management systems had more stable aggregates and SOC than conventionally plowed fields; much of

Fig. 6.29 Combine harvesting of soybeans followed by no-till planting of cotton in Oxisols in Mato Grosso, Brazil. Courtesy of Alysson Paolinelli

the SOC was in the 2 mm macroaggregate size class (Castro Filho *et al*. 2002). No-till planting in Brazil covered about 32 million hectares in 2015 (Motter and Almeida 2015).

Still, other barriers remained. Year-round soil cover did not occur because cropland was not used during the 6-month dry season, resulting in weed growth and wind erosion. In lands devoted to grazing livestock, pastures degrade with time, and cattle production declines, with major live-weight losses, during the dry season. Embrapa researchers then developed an integrated crop–livestock system (*integração lavoura–pecuária*), one of the most intelligent rainfed tropical farming systems, which reached about 700 000 hectares in 2003 (Kluthcouski *et al*. 2003), over 1.5 million hectares in 2009 (Alfredo Lopes, personal communication, 2010) and 11.5 million hectares in 2017. The system, as I saw in a 1500-ha farm in Baldim, Minas Gerais, in 2008, is fully described in the chapter on livestock (Chapter 18) and summarized below.

Starting from a degraded pasture, farmers plow conventionally, incorporating the necessary amendments and fertilizers down to 30 cm, and planting maize. Seeds of *Brachiaria ruziziensis* are broadcast over the maize rows. Maize is harvested by small combines, leaving the crop residues on the surface, through which the stoloniferous *Brachiaria* grows. Cattle start grazing during the dry season, and continue for about 18–24 months. When farmers decide it is time to rotate back to crops, because the pasture begins to degrade, grazing pressure is increased to reduce pasture biomass. Soybeans are then planted with no-till machinery (Fig. 6.28), combine-harvested, and the cycle repeats itself with an average duration of 4 years. By creating a biological superstructure *in* and *over* the soil, comprised of deep-root biomass and a constant vegetative cover over the soil surface, a year-round productive land-use system becomes possible. It was remarkable to see well-nourished heifers gaining weight by grazing pastures that had received no rain in 5 months.

This is intelligent tropical agriculture and what conservation agriculture is all about. Notice that an essential component was to do conventional tillage first, in order to restore soil fertility, which could not be accomplished with strict conservation agriculture guidelines.

In the northern part of the Cerrado, conservation agriculture is practiced at a very large scale. The spectacular Fig. 6.29 shows the simultaneous harvesting of soybeans followed by no-till planting of cotton in Oxisols in Mato Grosso State, Brazil. This is another example of intelligent tropical soil management using conservation agriculture with high capital inputs in Oxisols, which were believed by many to be unsuitable for agriculture (Chapter 3).

Soils with similar core properties (Ultisols, Oxisols and some Andisols) have also been found to be suitable for conservation agriculture in smallholder tropical farming systems. The conservation agriculture movement has also taken hold in what are called small farms in Latin America (5–20 hectares of cropland), but are really medium-sized from a pan-tropical perspective. Many systems are described by Buckles *et al*. (1998ab), Eilittä *et al*. (2004) and Goddard *et al*. (2008), most of which occur in two regions, the hillsides of Mesoamerica and the subtropical state of Santa Catarina, Brazil, with adjacent regions of Paraguay.

A remarkable one is *abonera*, a maize–mucuna relay inter-cropping system, now widespread in the humid tropical hillsides of Mesoamerica, where the soils are mainly Ultisols (Triomphe and Sain 2004). Farmers plant a fallow of *Mucuna pruriens* (velvet bean, *frijol terciopelo*) during the first rains, and later maize, using a planting stick in the slashed, thick mucuna mulch at the end of the rainy season. The fast-growing herbaceous legume reestablishes itself though natural reseeding near maize harvest time; it is allowed to regrow but it is always slashed prior to the next maize planting.

Mucuna provides a continuous cover throughout the year, prevents erosion in very steep slopes and controls weeds including the aggressive *Rottboellia cochinchinensis*. If well established, mucuna fixes nitrogen and reduces labor,

Fig. 6.30   Profiles of the top 30 cm of the same loamy, gravelly Alfisol at IITA, Ibadan, Nigeria, after 6 years of conventional tillage (left) and no-till (right) in Rattan Lal's plots. Conventional tillage caused the loss of primary soil particles from the topsoil, thus increasing the gravel content. The soil under no-till certainly looks better.

and farmers are able to take advantage of the higher prices of the dry-season maize. But if mucuna is not slashed in a timely fashion, it can grow over the maize and increase labor at harvest. Maize yields increased by about 50 percent in these systems (Triomphe and Sain 2004).

Loamy, Gravelly Alfisols (*LCr+*, *SL*, *LC* soils)
Loamy, gravelly Alfisols without steep slopes are very common throughout subhumid West Africa and are also suitable for conservation agriculture. In fact, Rattan Lal pioneered no-till research in the tropics in such soils (Lal *et al.* 1978, 1979, Lal 1985, 1986, Opara-Nadi and Lal 1987, Lal 1989, 1991, Kayombo and Lal 1993, Lal 1995, 1999). Lal and colleagues observed that conventional tillage in these soils caused rapid runoff, erosion and in some cases compaction, while no-till avoided much of this damage (see Fig. 6.30).

In these gravelly, loamy Alfisols, Lal (1985) observed that water retention at −10 kPa increased from 14.7 percent to

17.5 percent in the no-till watershed after 6 years of continuous mechanized farming, whereas it decreased from 17.7 percent to 13.8 percent in the plowed watershed, both at 0–10 cm depth.

Entisols and Inceptisols of the Indo-Gangetic Plain
Soils of the Indo-Gangetic Plain, mostly Entisols and Inceptisols, show a broad textural gradient, from sandy soils at the western end in the Pakistani and Indian Punjab, to loamy soils in the middle in Uttar Pradesh, Haryana and Bihar in India and Nepal, to clayey soils in West Bengal and Bangladesh at the eastern end. In the cradle of the Asian Green Revolution, most farmers practice a rice–wheat annual rotation, nowadays with excessive irrigation and excessive tillage that have resulted in yield stagnation, salinization, micronutrient deficiencies and severe aquifer depletion (Gupta *et al.* 2003). Bhan and Bharti (2008) described the development of no-till plus fertilizer drills for planting

wheat into rice stubble. No-till for wheat does away with intensive and repeated plowing of farmers' fields, is increasing wheat yields, reducing water use by as much as 50 percent and requiring less fuel for running tractors (Harrington and Erenstein 2005). These and other forms of minimum tillage cover 1.9 million hectares in the Indo-Gangetic Plain, about 15 percent of the 13 million hectares under this system in Pakistan, India, Nepal and Bangladesh (Ladha *et al.* 2003, Derpsch 2008).

But the challenge is the rice crop, which is grown in bunded paddies, with land preparation by puddling. Puddling is designed to destroy soil structure in order to decrease water losses by percolation (Sanchez 1973). Puddled soils of loamy texture often develop a plow pan below the puddled layer, and dry slowly. The clayey ones become hard and difficult to till, either by conventional or conservation tillage. Puddling delays the timing of wheat planting, while waiting for the soil to be at the moisture content appropriate for planting (Sharma *et al.* 2003). This farming system has the paradox of first destroying soil structure to grow rice and then restoring it to grow wheat, all in a 2-month window.

Puddled soils regain their original structure more quickly in sandy soils than in clayey soils. There is little rice yield response to puddling when the soil is able to remain flooded during rice growth (Sanchez 1973), and there are tradeoffs between the intensity of puddling and weed growth. The more intense the puddling, the greater the weed destruction (Sharma *et al.* 2003). There is more discussion of puddling in Chapter 17.

Unfortunately, most of the rice straw is harvested for livestock feed or burned *in situ*, and cattle manure is mostly used as fuel for cooking, so there is little crop residue for conservation agriculture. The same happens with the wheat straw.

Conservation agriculture, therefore, must look at the cropping system, with the possibility of eliminating puddling in the soils with good water control, leaving as much rice and wheat stubble on the soil as possible, incorporating no burning practices and using no-till planters, as shown by Bhan and Bharti (2008). Unlike the previous examples, this one is still work in progress at the time of writing.

Loamy and Clayey Alfisols – The Zambian Model
A different form of conservation agriculture is being practiced by over 180 000 small-scale farmers (less than 5 hectares) in the subhumid to semiarid central and southern provinces of Zambia (Peter Aagard, personal communication, 2009). These are areas of gentle topography, which are dominated by loamy to clayey Alfisols, without gravel and with permanent charge. Farmers dig micro-basins with a specially designed implement (Fig. 6.31), laid out in a precise grid that disturbs about 10 percent of the field, thus meeting the definition of conservation tillage. These 30-cm-long basins are dug by hand with hoes, at the start of the dry

Fig. 6.31 Implement used to dig the permanent planting basins near Shimubala, southern Zambia.

season, when the soil is still soft. This reduces the labor needs at the busy start of the rainy season, allowing time for early planting and early weeding. The basins catch the first and erratic rains that allow early planting, and are dug up again in following years, becoming a permanent feature of these fields. A variant of the system is using ox-drawn rippers in lines, instead of hand hoeing, for the 10 percent of farmers that own oxen or can hire a tractor equipped with a reaper. In either case, crop residues remain in the field. Improved seeds, precisely placed fertilizers and crop rotations with legumes are also key components of the system.

Maize yields increased by 1.5 t/ha, probably doubling the yields under conventional tillage. Haggblade and Tembo (2003) broke down this yield increase as follows: 0.4 t/ha from early planting; 0.7 t/ha from water harvesting in the microbasins; and the remaining 0.4 t/ha from higher doses of fertilizer and high-yielding varieties. I saw that a nearby farmer who did not use conservation tillage and planted late, with no fertilizer, obtained basically no yield.

The curse of rainfed farms is late planting. By preparing the land during several operations during the dry season, applying the correct amounts of properly placed fertilizers, dry planting before the rains, having the basins to capture rainfall and controlling weeds with a herbicide that does not have a residual effect, these microbasins become permanent. In some systems, the maize is rotated with peanuts or soybeans, leaving the maize stover on top of the soil. This is probably the most practical form of conservation agriculture I have seen in Africa. It meets all five requirements of conservation – minimum tillage, keeping the soil covered, herbicide use, crop rotation and appropriate fertilization. This form of conservation agriculture is another example of intelligent agriculture.

6.8.3 Soils in Which Conservation Agriculture is Difficult

Wet Soils (*g* Soils)
No-till is not advisable for poorly drained soils that are often waterlogged at the surface (Derpsch 2005). Puddling, the

extreme opposite of no-till, is the main tillage method for paddy soils (see Chapter 17). The purpose of cultivation for wetland rice is the opposite of conservation agriculture: destroy the soil's structure. This is not applicable to upland rice, where rice is grown under aerobic conditions like any other cereal.

Vertic Soils (v Soils)

Vertisols pose particular challenges because of their hardness while dry, and rapid swelling when the rains start, which often results in waterlogging. In parts of India and Ethiopia, no planting is done on Vertisols during the rainy season; farmers wait until the soil dries, till and then farm on residual moisture (Syers *et al.* 2001). Tillage is usually done by animal power or tractors. Research in India (Krantz *et al.* 1979) and in Ethiopia (Astatke and Jabbar 2001) resulted in the development of an oxen-driven broadbed maker that produces shallow (20 cm) furrows for drainage and 80–120-cm-wide beds. Drainage water is channeled downhill. This necessitates farmers in the catchment developing these canals together so no one gets flooded from the field higher up. Excess water can be stored in ponds or microdams. Runoff is halved, while soil erosion is drastically reduced. Wheat yields in Ethiopia with the broadbed and accompanying agronomic technologies have averaged 1.5–3.0 t/ha as compared with the traditional 0.6–0.7 t/ha (Jabbar *et al.* 2001).

If reduced tillage can be done during the short period when Vertisols are neither too wet nor too dry and hard for the heavy no-till planting machines to operate well, then conservation agriculture is possible, provided that enough crop residues are produced to cover the soil year-round, and the crops are fertilized.

Structurally Inert Soils (SLz Soils)

Conservation agriculture is unlikely to work in soils that develop surface sealing. The ample literature from the Sahel, Botswana and Australia indicates that some form of shallow tillage is necessary to break the crusts and allow water to infiltrate and seeds to emerge. Opening a slit on the soil surface leaves the rest of the soil surface-sealed. In such soils in Senegal, the bulk density of the first few centimeters decreased from 1.6 t/m^3 to 1.4 t/m^3 with shallow hoe cultivation to break the crusts. With tractor plowing, the same values were reached to a depth of 10–30 cm (Charreau and Nicou 1971, Charreau 1972), essentially overcoming hardsetting where it also occurs. Significant crop yield increases were attained. The results are shown in Table 6.22. In these soils, decreases of 0.1 t/m^3 in bulk density have a beneficial effect on root development and yields. Root density in the top 20 or 30 cm was closely correlated with grain yields (Nicou 1972).

Mounds for Root Crops

Large mounds, up to 40 cm high and 50 cm in diameter, are built to grow yams (*Dioscorea* spp.) in sandy and loamy Alfisols of humid West Africa, in soils otherwise suitable to

Table 6.22	Positive crop yield responses to shallow hoe tillage to break the crust in structurally inert sandy Alfisols in Senegal. Adapted from Charreau and Nicou (1971) and Charreau (1972).

Crops	No-till	Shallow hoe tillage
	Grain yields (t/ha)	
Sorghum	1.93	2.42
Maize	2.59	3.49
Upland rice	1.16	2.36
Peanuts	1.45	1.77

conservation agriculture. This requires an enormous amount of manual tillage, and the reason for it is to provide a loose soil for these large tubers to grow, considering the subsoil is often gravelly and clayey. In Nitisols (Rhodic Haplustalfs) of Cuba, the same yams grow well in conventionally plowed and furrowed land, as the soil structure is much better.

6.8.4 Small-Scale Farms in Africa

Considering the wide array of soils where conservation agriculture is feasible, as well as the instances where it is unlikely to work, why has this practice not taken root in smallholder tropical African farms as it has in large swathes of smallholder farms in tropical Asia and Latin America?

Conservation agriculture in smallholder African farms faces three major obstacles: the energy needs of planting equipment, keeping crop residues in the field and the need for herbicides. Results from African research are neither clear nor consistent (Giller *et al.* 2009). What is clear is that conservation tillage decreases runoff and erosion (Lal 1986, Kayombo and Lal 1993).

Giller *et al.* (2009), in their "heretic" review, indicate several tradeoffs that the smallholder African farmer often has to make to shift to conservation agriculture. Is mulching the most sensible, efficient or profitable use of crop residues? Is there a yield penalty in the short term and a yield gain in the long term? Does conservation agriculture save labor? Does conservation agriculture increase SOM and soil fertility? Also, can they afford herbicides and no-till machinery?

In my view, smallholder African farmers need to obtain no-till planting machinery (ideally the small ones used in southern Brazil, some of them pulled by cattle), keep at least half of the crop residues in the field and shift from hand weeding to herbicides. Farm service companies can rent suitable equipment to smallholders. In fact, there is an "Uber"-like company that rents farm equipment to smallholder farms in Tanzania (Cheryl Palm, personal communication, 2017).

The results of Aagard's (2009) southern Zambia model shows that it can be done in farms of 1–5 hectares and taken up at scale, avoiding the need to purchase no-till planting machinery. The labor required to plant by hoe (Fig. 6.16) or to make ridges and furrows every year (Fig. 6.17) is so deeply ingrained in farmers with 1 hectare or less that only a comprehensive effort will be effective. One that addresses not only tillage, but crop residue use, crop rotation and herbicide and fertilization, with a financial stimulus package to cover the additional costs and probably the initially lower yields.

Farmers get paid for soil conservation in many rich countries as an ecosystem service. Certainly the millions of smallholder African farmers can benefit in a similar way.

Conservation agriculture is a major and positive paradigm shift in world agriculture, and the larger farms of the tropics are already benefiting. The challenge is for the small-holder farmers to benefit as well.

6.9 Summary and Conclusions

- Soil texture, mineralogy and soil organic matter (SOM) control most physical soil processes.
- The overarching management principle is to keep the soil covered throughout the year with a vegetative layer.

Soil Depth
- The most obvious physical limitation – insufficient soil depth for adequate root development – is often ignored. Physical barriers to root development are probably less common in the tropics than in the temperate region.

Soil Temperature
- Extreme soil temperatures, either too high or too low, are a limiting factor in certain areas of the tropics. The solution is usually to mulch with various materials, depending on whether temperatures need to be decreased or increased. Plastic mulches are increasingly used.

Soil Structure
- Soil structure is the size, shape and arrangement of solids and voids, the continuity of voids and their capacity to retain and transmit air and water.
- Water-stable aggregates give soils a good structure. Aggregates are generally grouped in two sizes: macroaggregates (> 250 µm), with macropores between them, generally larger than 50 µm in diameter, which drain gravimetric water; and microaggregates (50–250 µm), with micropores ranging from 0.2 to 50 µm in diameter, which hold water at -10 kPa to -1500 kPa of soil moisture tension. These micropores, therefore, hold most of the water available to plants.
- Texture, mineralogy and SOM determine soil aggregation. In sandy and loamy sand textures (< 15 percent clay), the primary particles tend to remain single-grained because the large macropores between them make

microorganisms rapidly respire away organic inputs as carbon dioxide, instead of decomposing them slowly to form SOM by binding the primary particles into aggregates. It takes loamy textures (15–35 percent clay) and clayey ones (> 35 percent clay) to make water-stable aggregates.
- The highly aggregated structure of Oxisols, Andisols and oxidic families of Ultisols and Alfisols presents tremendous advantages and serious disadvantages. The very stable aggregates that are coated with oxides and SOM extend the time period of land preparation because they drain gravitational water, much like sands. Strong aggregation also diminishes compaction and erosion problems. The disadvantages lie in the low range of available moisture of these soils in spite of their capacity to hold large quantities of water at high tensions inside the aggregates. Many clayey Oxisols are actually "droughty" soils, and leaching in these soils is considerable.
- Ultisols and Alfisols that are not oxidic have a less stable structure that presents different management problems. Exposure and cultivation can lead to soil compaction, runoff and erosion. The moisture range suitable for tillage operations is narrower than in the case of Oxisols. On the positive side, many of these soils hold more available water in their profiles than do Oxisols.
- Structurally inert Alfisols with high fine-sand and silt content, low SOM and kaolinitic clay mineralogy (z soils in the FCC system), typical of many semiarid areas, behave very differently from other Alfisols, developing surface sealing that impedes rainfall infiltration and causes major runoff.
- The fourth large group of tropical soils consists of loamy to clayey soils with permanent-charge mineralogy, classified as Vertisols, Aridisols, Mollisols and many Entisols and Inceptisols. Among them, Vertisols present special physical limitations due to shrinking and swelling and their narrower moisture range that is suitable for tillage operations. Management practices developed in the temperate region for such soils should be applicable, with a minimum of adjustment, to tropical soils with permanent-charge mineralogy.

Soil Compaction
- Soil compaction is a major problem in the tropics because of excessive tillage, overgrazing and even foot traffic. The major forms are surface sealing and crusting, hardsetting and plow pans.
- The structurally inert Alfisols are very susceptible to surface sealing when wet and to crusting when dry. Surface sealing and crusting prevents seedling emergence, sharply reduces infiltration, decreases water storage in the soil and triggers runoff and hence erosion. Unlike other kinds of soil compaction, surface sealing is largely due to raindrop impact.
- Hardsetting occurs when much of the entire soil profile becomes very hard as it dries, such that it is virtually

impossible to cultivate until it is rewetted. Hardsetting in a cultivated soil usually involves slumping and an increase in bulk density, without the application of an external force, making this process a unique form of natural soil compaction. Hardsetting happens mainly in soils that have few water-stable aggregates.

- Tillage and farm machinery traffic can also induce subsoil compaction in the form of a plow pan. The depth of the pan varies from 10 cm to 60 cm and is usually several centimeters thick. Plow pans can develop in most tropical soils except Vertisols, where shrinking and swelling through the profile prevents their formation.

Soil Water

- The differences in structure among broad types of tropical soils result in dramatic differences in their water-retention properties. Sandy soils empty their pores of gravitational water at tensions close to −10 kPa, while soils with smectitic clays do this at −50 kPa. This is what is traditionally known as "field capacity," but the tensions vary from the classic 0 kPa to −30 kPa definition.
- The moisture-retention pattern of a clayey, well-aggregated Oxisol is a hybrid of these two. These Oxisols hold as much water as smectitic clays, up to approximately −10 kPa, but drain their macropores at about that tension, thus reaching field capacity as sands do. Oxisols act like sands at low tensions because of their strong, sand-sized macroaggregates, but hold water like smectitic clays at higher tensions. Therefore, they have a narrower available water range than other clays. The most commonly accepted definition of Oxisol field capacity is about −10 kPa.

Soil Erosion

- Soil erosion is often the most visible evidence of land degradation and is a major problem in much of the tropics. Soil erosion by water is a function of five factors: rainfall erosivity, soil erodibility, slope gradient and length, soil cover and protective structures such as terraces. Rainfall erosivity is generally higher in the tropics than in the temperate regions because higher air temperatures provide more energy.
- Soils dominated by low-activity clays and iron oxides (Oxisols, Ultisols) as well as allophane (Andisols) have generally lower soil erodibility than soils with high-activity clays (Aridisols, Mollisols, Vertisols). The most erodible soils are soils with 40–60 percent silt content, uncommon in the tropics.
- Land degradation in many policy studies equals soil erosion. To our shame, many economists use the straight soil-loss data from the Wischmeier plots as representative of real conditions at the field, watershed and even national scales. Most soil scientists know well that this methodology overestimates or sometimes underestimates erosion losses due to the small size of these plots. But what is eroded from one spot is most frequently deposited

in another one in the same field or watershed, often leading to no losses at those scales. Soil erosion, therefore, is better estimated at the watershed (catchment) scale.

Soil and Water Conservation Practices

- Soil conservation practices are generally of two types: providing protective barriers against erosion and keeping a vegetative cover over the soil. Planting along the contours, instead of up and down the slope, is a sound practice, but the advantage of contour cultivation is more evident for steep slopes. Planting trees or stoloniferous grasses along the contour provides effective barriers against erosion. "Biological terraces" are produced by the erosion process within the contour hedges, with the tree or grass growth keeping up with the higher soil surface at the lower end – something stone bench terraces cannot do. Steep back-slope terraces (*fanya juu*) are effective and widespread in East Africa. Ridge and furrow systems, including tied ridges and trench bunds, when laid along the contour, hold water for a longer time in most soils.
- When cropland is next to hills or scarps, the potential for capturing runoff and storing it in the subsoil can be very significant. Water can be channeled using stone bunds and percolation ponds, where water is stored in the subsoil and recovered by shallow wells downstream. Another major source of rainfall capture are the ditches along roads.
- The restoration of gullied lands involves larger-scale efforts – stone and gabion check dams. They successfully capture sediments and prevent new gullies from being formed that could threaten current fields. Gully bottoms are generally fertile and are often planted.

Conservation Agriculture

- Conservation agriculture is based on five components: minimum or no tillage, crop residue return, herbicide use, crop rotation and appropriate fertilizer use. Conservation agriculture is often equated to minimum or no tillage (no-till), ignoring the other four components, and causing confusion in the literature. Recent analyses suggest that conservation agriculture does not always provide the benefits that are widely publicized.
- Oxisols, loamy and clayey Alfisols, Ultisols, Andisols and many Inceptisols and Entisols are suitable for conservation tillage, provided they are not poorly drained. Conservation agriculture is very difficult to do in wet soils, vertic soils and in soils susceptible to surface sealing (*g*, *v* and *z* soils in the FCC system).
- When only the no-till component is used, a meta-analysis found that crop yields were 11 percent lower than with conventional agriculture. When no-till was combined with residue return the conservation agriculture yield penalty was reduced to about 6 percent, and when the three components were applied, the difference was reduced to practically nothing after 10 years. The two remaining components, herbicide use and

adequate fertilization, were practiced uniformly in this meta-analysis.

- Crop residue return is the most critical component because it provides new carbon to the soil as well as year-round soil cover, while the effects of crop rotation are more often related to weed, pest and disease control.
- Soil organic carbon (SOC) increases in the top 10 cm of the soil after 5 to 10 years of continuous zero tillage, particularly if it is accompanied by crop residue return.
- The increase in SOC under conservation agriculture results in higher biological activity, including that of macrofauna such as earthworms and termites, as well as improved nutrient cycling. Plow pans are eventually eliminated by root and macrofauna activity. However, the heavy no-till planters sometimes cause soil compaction. Occasional deep tillage is often needed to eliminate compacted layers.
- No-till and leaving crop residues partly on the soil surface decreases runoff and soil erosion by at least 10 times. This is the clearest effect of conservation agriculture. The large decrease in runoff and erosion losses means that additional water can be stored in the soil with conservation agriculture.
- Carbon sequestration by conservation agriculture is considered one of the main pillars of climate-smart agriculture. The data, however, do not provide a clear trend, due to considerable variation in carbon sequestration in the top 40 cm due to differences in texture, mineralogy, initial SOM content, the amount of crop residues added and crop rotation schemes. Data on nitrous oxide and methane emissions do not show a clear trend either. Therefore, the climate regulation function of conservation agriculture cannot be taken for granted.
- Conservation agriculture works well in many large-scale mechanized farms, but it is generally difficult to implement in smallholder farms, which lack sufficient crop residue return and do not use herbicides. Nevertheless, there are successful conservation agriculture systems practiced in small farms of Central America and in southern Zambia.

References

Aagard P. 2009. *Could the Lessons from 14 Years of Promoting Conservation Agriculture in Zambia be of Value to Kenya and Other Countries in the Region?* Conservation Farming Unit, Lusaka.

Adiningsih JS and A Syarifuddin Karama. 2004. *A Sustainable Upland Farming System for Indonesia*. Center for Soil and Agroclimate Research, Bogor.

Agus F, DK Cassel and DP Garrity. 1997. Soil-water and soil physical properties under contour hedgerow systems on sloping Oxisols. *Soil and Tillage Research* 40: 185–199.

Alegre JC, DK Cassel and DE Bandy. 1986. Effects of land clearing methods and subsequent management on soil physical properties of an Ultisol in the Amazon Basin of Peru. *Soil Science Society of America Journal* 50: 1379–1383.

Alegre JC and DK Cassel. 1996. Dynamics of soil physical properties under alternative systems to slash-and-burn. *Agriculture, Ecosystems and Environment* 58: 39–48.

Alegre JC and MR Rao. 1996. Soil and water conservation by contour hedging in the humid tropics of Peru. *Agriculture, Ecosystems and Environment* 57: 17–25.

Alegre JC and D Keith Cassel. 1999. *Intensive Soil Management in the Humid Tropics. SM-CRSP Technical Bulletin 99–1*. North Carolina State University, Raleigh, NC.

Astatke A and MA Jabbar. 2001. Low-cost animal-drawn implements for Vertisol management and strategies for land-use intensification. *The Sustainable Management of Vertisols*, JK Syers, FWT Penning de Vries and P Nyamudeza (eds.). CABI Publishing, Wallingford, pp. 189–201.

Banda AZ, JA Maghembe, DN Ngugi and VA Chome. 1994. Effect of intercropping maize and closely spaced *Leucaena* hedgerows on soil conservation and maize yield on a steep slope at Ntcheu, Malawi. *Agroforestry Systems* 27: 17–22.

Barnett AP, JR Carrecker and F Abruña. 1972. Soil and nutrient losses in runoff with selected crop treatments in tropical soils. *Agronomy Journal* 64: 391–395.

Bhan S and VK Bharti. 2008. Conservation tillage in Indian agriculture. *No-till Farming Systems. Special Publication 3*, T Goddard, MA Zoebisch, YT Gan, W Ellis, A Watson and S Sombatpanit (eds.). World Association of Soil and Water Conservation, Bangkok, pp. 197–206.

Blanco-Canqui H and R Lal. 2007. Impacts of long-term wheat straw management on soil hydraulic properties under no-tillage. *Soil Science Society of America Journal* 71: 1166–1173.

Brady NC and RR Weil. 2008. *The Nature and Properties of Soils*, 14th edition. Pearson Prentice Hall, Upper Saddle River, NJ.

Briggs LJ and HL Shantz. 1914. Relative water requirements of plants. *Journal of Agricultural Research* 3: 1–63.

Briones AA and JG Veracion. 1965. Aggregate stability of some red soils of Luzon. *Philippine Agriculture* 48: 61–81.

Bronick CJ and R Lal. 2005. Soil structure and management: A review. *Geoderma* 124: 3–22.

Buckles D, B Triomphe and G Sain. 1998a. *Cover Crops in Hillside Agriculture: Farmer Innovation with Mucuna*. International Development and Research Center, Ottawa.

Buckles D, A Eteka, O Osiname, M Galiba and G Galiano (eds.). 1998b. *Cover Crops in West Africa: Contributing to Sustainable Agriculture*. International Development Research Center, Ottawa.

Cagauan B and G Uehara. 1965. Soil anisotropy in relation to aggregate stability. *Soil Science Society of America Journal* 29: 198–200.

Carrasco DA and SG Witter. 1993. Constraints to sustainable soil and water conservation: A Dominican Republic example. *Ambio* 22: 347–350.

Castro Filho C, A Lourenço, MDF Guimarães and ICB Fonseca. 2002. Aggregate stability under different soil management systems in a red Latosol in the state of Paraná, Brazil. *Soil and Tillage Research* 65: 45–51.

Charreau C. 1972. Problemes poses par l'utilisation agricole des sols tropicaux par des cultures annuelles. *Agronomie Tropicale* 27: 905–929.

Charreau C and R Nicou. 1971. L'amelioration du profil cultural dans les sols sableux et sablo-argileux de la zone tropicale seche Ouest-Africaine et sis incidence agronomiques. *Agronomie Tropicale* 26: 1183–1247.

Chauvel A, M Grimaldi and D Tessier. 1991. Changes in soil pore space distribution following deforestation and revegetation: An example from the central Amazon Basin. *Forest Ecology and Management* 38: 259–271.

Cohen MJ, KD Shepherd and MG Walsh. 2005. Empirical reformulation of the universal soil loss equation for erosion risk assessment in a tropical watershed. *Geoderma* 124: 235–252.

Coughland KJ and CW Rose (eds). 1997. *A New Soil Conservation Methodology and Application to Cropping Systems in Tropical Steeplands. ACIAR Technical Report 40*. Australian Centre for International Agricultural Research, Canberra.

Craswell ET, JV Remenyi and LG Nallana (eds). 1985 *Soil Erosion Management: Proceedings of a Workshop held at PCARRD, Los Baños, Philippines, 3–5 December 1984. ACIAR Proceedings 6*. Australian Centre for International Agricultural Research, Canberra.

Cumming DHM and GS Cumming. 2003. Ungulate community structure and ecological processes: Body size, hoof area and trampling in African savannas. *Oecologia* 134: 560–568.

Deckers J, O Spaargaren and F Nachtergaele. 2001. Vertisols: Genesis, properties and soilscape management for sustainable development. *The Sustainable Management of Vertisols*, JK Syers, FWT Penning de Vries and P Nyamudeza (eds.). CABI Publishing, Wallingford, pp. 3–20.

Dehn M. 1995. An evaluation of soil conservation techniques in the Ecuadorian Andes. *Mountain Research and Development* 15: 175–182.

Denef K, J Six, R Merckx and K Paustian. 2002. Short-term effects of biological and physical forces on aggregate formation in soils with different clay mineralogy. *Plant and Soil* 246: 185–200.

Derpsch R. 2005. The extent of conservation agriculture adoption worldwide: Implications and impact. *III World Congress on Conservation Agriculture: Linking Production, Livelihoods and Conservation, Nairobi, 3–7 Oct 2005*. African Conservation Tillage Network, Nairobi.

2008. No tillage and conservation agriculture: A progress report. *No-Till Farming Systems. Special Publication 3*, T Goddard, MA Zoebisch, YT Gan, W Ellis, A Watson and S Sombatpanit (eds.). World Association of Soil and Water Conservation, Bangkok, pp. 7–39.

Eilittä M, J Mureithi and R Derpsch (eds.). 2004. *Green Manure/Cover Crop Systems of Smallholder Farmers: Experiences from Tropical and Subtropical Regions*. Kluwer, Dordrecht.

El-Swaify SA and EW Dangler. 1982. Rainfall erosion in the tropics: A state of the art. *ASA Special Publication* 43: 1–25.

Ella VB. 2005. Simulating soil erosion and sediment yield in small upland watersheds using the WEPP model. *Land Use Change in Tropical Watersheds: Evidence, Causes and Remedies*, I Coxhead and G Shively (eds.). CABI Publishing, Wallingford, pp. 109–125.

Emerson WW. 1995. Water-retention, organic-C and soil texture. *Australian Journal of Soil Research* 33: 241–252.

Escobar G, R Jurado y R Guerrero. 1972. Propiedades físicas de algunos suelos derivados de ceniza volcánica del Altiplano de Pasto, Nariño, Colombia. *Turrialba* 22: 338–346.

Eswaran H and R Drees. 2002. *Soil Under a Microscope: Evaluating Soils in Another Dimension*. Department of Soil & Crop Science, Texas A & M University, College Station, TX.

FAO. 2001. *Conservation Agriculture: Case studies in Latin America and Africa. FAO Soils Bulletin 78*. Food and Agriculture Organization of the United Nations, Rome.

Flanagan DC and MA Nearing (eds). 1995. *USDA Water Erosion Prediction Project Hillslope and Watershed Model Documentation. Report 10*. USDA–ARS National Soil Erosion Research Laboratory, West Lafayette, IN.

Forsythe W and R Diaz-Romeu. 1969. La densidad aparente del suelo y la interpretación del análisis de laboratorio para el campo. *Turrialba* 19: 128–131.

Foster GR, WC Moldenhauer and WH Wischmeier. 1982. Transferability of US technology for prediction and control and erosion in the tropics. *ASA Special Publication* 43: 135–149.

Fullen MA. 2002. Improving crop productivity and agro-environmental sustainability on fragile slopes in the highlands of South China and Thailand. *Man and Soil at the Third Millennium*, JL Rubio, RPC Morgan, S Asins and V Andreu (eds.). Geoforma, Valencia, pp. 319–330.

Gaiser T, F Graef and JC Cordeiro. 2000. Water retention characteristics of soils with contrasting clay mineral composition in semi-arid tropical regions. *Australian Journal of Soil Research* 38: 523–536.

Garrity DP. 1993. Sustainable land use systems for the sloping lands of Southeast Asia. *ASA Special Publication* 56: 41–66.

1996. Tree–soil–crop interactions on slopes. *Tree–Crop Interactions: A Physiological Approach*, CK Ong and P Huxley (eds.). CABI Publishing, Wallingford, pp. 299–318.

Garrity DP and AR Mercado. 1994. Nitrogen fixation capacity in the component species of contour hedgerows: How important? *Agroforestry Systems* 27: 241–258.

Giller KE, E Witter, M Corbeels and P Tittonell. 2009. Conservation agriculture and smallholder farming in Africa: The heretics' view. *Field Crops Research* 114: 23–34.

Giller KE, M Corbeels, J Nyamangara, B Triomphe, F Affholder, E Scopel and P Tittonell. 2011. A research agenda to explore the role of conservation agriculture in African smallholder farming systems. *Field Crops Research* 124: 468–472.

Goddard T, M Zoebisch, Y Gan, W Ellis, A Watson and S Sombatpanit. 2008. *No-till Farming Systems. Special Publication 3*. World Association of Soil and Water Conservation, Bangkok.

Gonzalez-Erico E, EJ Kamprath, GC Naderman and WV Soares. 1979. Effect of depth of lime incorporation on the growth of corn on an Oxisol of central Brazil. *Soil Science Society of America Journal* 43: 1155–1158.

Grewal SS and NT Singh. 1974. Effect of organic mulches on the hydro-thermal regime of soil and growth of potato crop in northern India. *Plant and Soil* 40: 33–47.

Grohman F. 1960. Distribução de tamanho de poros en tres tipos de solos do Estado de São Paulo. *Bragantia* 19: 319–328.

Gupta RK, RK Naresh, PR Hobbs, J Zheng and JK Ladha. 2003. Sustainability of post-green revolution: The rice–wheat cropping system in the Indo-Gangetic plains and China. *ASA Special Publication* 65: 1–26.

Haggblade S and G Tembo. 2003. *Conservation Farming in Zambia. Discussion Paper 108*. International Policy Research Institute, Washington, DC.

Hamza MA and WK Anderson. 2005. Soil compaction in cropping systems. A review of the nature, causes and possible solutions. *Soil and Tillage Research* 82: 121–145.

Harrington L and O Erenstein. 2005. Conservation agriculture and resource conserving technologies: A global perspective. *III World Congress on Conservation Agriculture: Linking Production, Livelihoods and Conservation, Nairobi, 3–7 Oct 2005*. African Conservation Tillage Network, Nairobi.

Hillel D. 2008. *Soil and The Environment: Crucible of Terrestrial Life*. Academic Press, Burlington, MA.

Hoyos N. 2005. Spatial modeling of soil erosion potential in a tropical watershed of the Colombian Andes. *Catena* 63: 85–108.

Hulugalle NR, J de Koning and PJ Matlon. 1987. *Soil and Water Conservation with Rock Bunds and Tied Ridges in the Sudan Savannah of Burkina Faso*. IITA–SAFGRAD Project, Ouagadougou, Burkina Faso.

IRRI. 1964. *Annual Report*. International Rice Research Institute, Los Baños.

Jabbar MA, T Mamo and MA Mohamed Saleem. 2001. From plot to watershed management: Experience in farmer participatory

Vertisol technology generation and adoption in highland Ethiopia. *The Sustainable Management of Vertisols*, JK Syers, FWT Penning de Vries and P Nyamudeza (eds.). CABI Publishing, Wallingford, pp. 173–186.

Juo ASR, JO Caldwell and BT Kang. 1994. Place of alley cropping in sustainable agriculture in the humid tropics. *Transactions 15th World Congress of Soil Science. Volume 7a*. International Society of Soil Science, Acapulco, pp. 98–109.

Kassie M, J Pender, M Yusuf, G Kohlin, R Bluffstone and E Mulugeta. 2007. *Impact of Soil Conservation on Crop Production in the Northern Ethiopian Highlands. Discussion Paper 733*. International Policy Research Institute, Washington, DC.

Kayombo B and R Lal. 1993. Tillage systems and soil compaction in Africa. *Soil and Tillage Research* 27: 35–72.

Kiepe P and MR Rao. 1994. Management of agroforestry for the conservation and utilization of land and water resources. *Outlook in Agriculture* 23: 17–25.

Kluthcouski J, LF Stone and H Adiar (eds.). 2003. *Integração Lavoura Pecuária*. Embrapa Arroz e Feijão, Santo Antônio de Goiás.

Kondo MK and MS Dias Júnior. 1999. Compressibilidade de três Latossolos em funcão da umidade de solo e uso. *Revista Brasileira de Ciência do Solo* 23: 211–218.

Krantz BA, J Kampen and SM Virmani. 1979. *Soil and Water Conservation and Utilization for Increased Food Production in the Semi-Arid Tropics*. International Crops Research Institute for the Semi-Arid Tropics, Patancheru.

Ladha JK, H Pathak, A Tirol-Padre and RK Gupta. 2003. Productivity trends in intensive rice–wheat cropping systems in Asia. *ASA Special Publication* 65: 45–76.

Lal R. 1974. Soil temperature, soil moisture, and maize yields from mulched and unmulched tropical soils. *Plant and Soil* 40: 121–143.

1975. *Role of Mulching Techniques in Tropical Soil and Water Management. IITA Technical Bulletin 1*. International Institute of Tropical Agriculture, Ibadan.

1976. *Soil Erosion Problems on an Alfisol in Western Nigeria and their Control. IITA Monograph 1*. International Institute of Tropical Agriculture, Ibadan.

1985. Soil erosion and its relation to productivity in tropical soils. *Soil Erosion and Conservation*, SA El-Swaify, WC Moldenhauer and A Lo (eds.). Soil Conservation Society of America, Ankeny, IA, pp. 237–247.

1986. Deforestation and soil erosion. *Land Clearing and Development in the Tropics*, R Lal, PA Sanchez and RW Cummings Jr. (eds.). Balkema, Leiden, pp. 299–315.

1989. Conservation tillage for sustainable agriculture: Tropic vs. temperate environments. *Advances in Agronomy* 42: 85–197.

1991. Soil structure and sustainability. *Journal of Sustainable Agriculture* 1: 67–92.

1995. *Tillage Systems in the Tropics: Management Options and Sustainability Implications. FAO Soils Bulletin 71*. Food and Agriculture Organization of the United Nations, Rome.

(ed.). 1999. *Soil Quality and Soil Erosion*. CRC Press, Boca Raton, FL.

Lal R, GF Wilson and BN Okigbo. 1978. No-till farming after various grasses and leguminous cover crops in tropical Alfisol: 1. Crop performance. *Field Crops Research* 1: 71–84.

1979. Changes in properties of an Alfisol produced by various crop covers. *Soil Science* 127: 377–382.

Lopes AS and E Daher. 2008. Agronegócio e recursos naturais no Cerrado: Desafios para uma coexistência harmónica. *IX Simpósio Nacional sobre o Cerrado e o Simpósio Internacional sobre Savanas Tropicais*. Embrapa, Brasília, pp. 35–71.

Lopes AS, S Wietholter, LRG Guilherme and CA Silva. 2004. *Sistema Plantio Direto: Bases Para o Manejo da Fertilidade do Solo*. Associação Nacional para Difusão de Adubos (ANDA), São Paulo.

Lugo-López MA and J Juárez. 1959. Evaluation of the effects of organic matter and other soil characteristics upon the aggregate stability of some tropical soils. *Journal of Agriculture of the University of Puerto Rico* 43: 268–272.

Lugo-López MA, J Juárez and JA Bonnett. 1968. Relative infiltration rates of Puerto Rican soils. *Journal of Agriculture of the University of Puerto Rico* 52: 233–240.

Lugo-López MA and R Pérez-Escolar. 1969. A mathematical approach to evaluating the influence of various factors on the stability of aggregates in Vertisols. *Journal of Agriculture of the University of Puerto Rico* 56: 307–317.

Maclean AH and TV Yager. 1972. Available water capacities in Zambian soils in relation to pressure plate measurements and particle size analysis. *Soil Science* 133: 23–29.

Malesu MM, AR Oduor and OJ Odhiambo (eds.). 2007. *Green Water Management Handbook: Rain Water Harvest For Agricultural Production And Ecological Sustainability. World Agroforestry Center Technical Manual 8*. ICRAF, Nairobi.

McKenzie N, K Coughland and H Cresswell. 2002. *Soil Physical Measurement and Interpretation for Land Evaluation: Australian Soil and Land Survey*. CSIRO, Canberra.

Millward AA and JE Mersey. 1999. Adapting the RUSLE to model soil erosion potential in a mountainous tropical watershed. *Catena* 38: 109–129.

Monengat C. 1991. *Plantas de Cobertura del SUELO. Características y Manejo de Pequeñas Propiedades*. Ed Chapecó, Santa Catarina.

Moran CJ and AB McBratney. 1992. Acquisition and analysis of three-component digital images of soil pore structure. I. Method. *Journal of Soil Science* 43: 541–550.

Motter P and HG de Almeida (eds.). 2015. *Plantio Direto: A Tecnologia que Revolucionou a Agricultura Brasileira*. Parque Itaipu, Foz do Iguaçú.

Moura FW and SW Buol. 1972. Studies of a *Latosol Roxo* (Eutrustox) in Brazil. *Experientiae* 13: 201–234.

Müller-Sämann K and JM Restrepo (eds.). 1997. *Conservacion de Suelos y Aguas en La Zona Andina. Hacia el Desarollo de un Concepto Integral*. CIAT, Cali.

Mullins CE, IM Young and AG Bengough. 1987. Hard-setting soils. *Soil Use and Management* 3: 79–83.

Mullins CE, DA MacLeod, KH Northcote, JM Tisdall and IM Young. 1992. Hardsetting soils: Behavior, occurrence and management. *Advances in Soil Science* 11: 38–108.

Nega H and PM Kimeu. 2002. *Low-Cost Methods of Rainwater Storage. RELMA Technical Report 28*. ICRAF, Nairobi.

Nicou R. 1972. *Synthese des Estudes de Physique du sol Realises par l'IRAT en Afrique Tropicale Seche. Seminar on Tropical Soils Research*. International Institute for Tropical Agriculture, Ibadan.

Nicou R and C Charreau. 1980. Mechanical impedance related to land preparation as a constraint to food production in the tropics. *Priorities for Alleviating Soil-Related Constraints to Food Production in the Tropics*, International Rice Research Institute, Los Baños, pp. 371–388.

Njoroge M and MR Rao. 1994. Barrier hedgerow intercropping for soil and water conservation on sloping lands. *Eighth International Soil Conservation Organization (ISCO) Conference, New Delhi, December 4–8*, Indian Association of Soil & Water Conservationists, Dehradun, pp. 1427–1441.

Nyamudeza P, OT Mandiringana, T Busanagavanye and E Jones. 1991. The development of sustainable management of Vertisols in the Lowveld area of southeastern Zimbabwe. *IBSRAM Newsletter* 20: 6–9.

Nyamudeza P, K Hussein and B Matibiri. 2001. Vertisol management in Zimbabwe. *The Sustainable Management of Vertisols*, JK Syers, FWT Penning de Vries and P Nyamudeza (eds.). CABI Publishing, Wallingford, pp. 139–153.

Nyssen J, J Poesen, M Haile, J Moeyersons and J Deckers. 2000. Tillage erosion on slopes with soil conservation structures in the Ethiopian highlands. *Soil and Tillage Research* 57: 115–127.

Nyssen J, M Haile, J Poesen, J Deckers and J Moeyersons. 2001. Removal of rock fragments and its effect on soil loss and crop yield. *Soil Use and Crop Management* 17: 179–187.

Nyssen J, J Poesen, J Moeyersons, E Lavrysen, M Haile and J Deckers. 2002. Spatial distribution of rock fragments in cultivated soils in northern Ethiopia as affected by lateral and vertical displacement processes. *Geomorphology* 43: 1–16.

Nyssen J, N Munro, M Haile, J Poesen, K Descheemaeker, N Harteweyn, J Moeyersons, G Govers and J Deckers. 2007. *Understanding the Environmental Changes in Tigray: A Photographic Record Over 30 Years. Tigray Livelihood Paper 3*. Mekelle University, Mekelle.

Opara-Nadi OA and R Lal. 1987. Effects of no-till and disc plowing with and without residue mulch on tropical root crops in southeastern Nigeria. *Soil and Tillage Research* 9: 231–240.

Palm CA, PA Sanchez, S Ahamed and A Awiti. 2007. Soils: A Contemporary Perspective. *Annual Review of Environment and Resources* 32: 99–129.

Palm C, H Blanco-Canqui, F DeClerck, L Gatere and P Grace. 2014. Conservation agriculture and ecosystem services: An overview. *Agriculture, Ecosystems & Environment* 187: 87–105.

Peltier R. 1993. *Les Terres Hardé: Caractérisation et Réhabilitation dans le Bassin du Lac Tchad. Cahiers Scientifiques*. CIRAD-Forêt, Nogent-sur-Marne.

Pereira HC. 1956. A rainfall test for structure in tropical soils. *Journal of Soil Science* 7: 68–74.

Pereira HC, PH Hosegood and M Dagg. 1967. Effects of tied ridges, terraces and grass leys on a lateritic soil in Kenya. *Experimental. Agriculture* 3: 89–98.

Pires LF. 2009. Pore system changes of damaged Brazilian Oxisols and Nitosols induced by wet–dry cycles as seen in 2-D micromorphologic image analysis. *Anais da Academia Brasileira de Ciências* 81: 151–161.

Pittelkow CM, X Liang, BA Linquist, KJ van Groenigen, J Lee, ME Lundy, N van Gestel, J Six, RT Venterea and C van Kessel. 2015. Productivity limits and potentials of the principles of conservation agriculture. *Nature* 517: 365–368.

Powlson DS, CM Stirling, BG Gerard, ML Jat, CA Palm, PA Sanchez and KG Cassman. 2014. Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change* 4: 678–683.

Pulleman MM, J Six, N van Breemen and AG Jongmans. 2005. Soil organic matter distribution and microaggregate characteristics as affected by agricultural management and earthworm activity. *European Journal of Soil Science* 56: 453–467.

Ravoof AA, WG Sanford, HY Young and JA Silva. 1973. Effects of root temperature and nitrogen carriers on total nitrogen uptake by pineapple. *Agronomy Abstracts* 1973: 194.

RELMA. 2005. *Managing Land: A Practical Guidebook for Development Agents in Ethiopia. Technical Handbook 36*. ICRAF, Nairobi.

Renard KG, GR Foster, GA Weesies, DK McCool and DC Yoder. 1997. *Predicting Soil Loss by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). Agriculture Handbook 703*. USDA, Washington, DC.

Resck DVS, JE da Silva, AS Lopes and LM da Costa. 2006. Management systems in northern South America. *Global Climate Change and Tropical Agroecosystems*, R Lal, JM Kimble and BA Stewart (eds.). CRC Press, Boca Raton, FL, pp. 169–196.

Resck DVS, EAB Ferreira, JDG dos Santos Júnior, MAC da Sá and CC Figueiredo. 2008. Manejo de Solo sob um Enfoque Sistêmico. *IX Simpósio Nacional sobre o Cerrado e o Simpósio Internacional sobre Savanas Tropicais*. Embrapa, Brasilia, pp. 417–473.

Reyes ED, NC Galvez and NB Nazareno. 1961. Lysimeter studies of Lipa clay loam grown paddy rice. I. Leaching losses of some soil constituents. *Philippine Agriculture* 45: 246–257.

Roose EJ. 1970. The relative importance of erosion, lateral and vertical drainage on present pedogenesis of ferralitic soil of central Ivory Coast. *Cahiers ORSTOM Série Pédologie* 8: 469–482.

Roose E. 1975. Use of the universal soil loss equation to predict erosion in West Africa. *Soil Erosion: Prediction and Control*, Soil and Water Conservation Society, Ankeny, IA, pp. 60–74.

Rosswell CJ. 1993. *SOILOSS: A Program to Assist in the Selection of Management Practices to Reduce Erosion. New South Wales Soil Conservation Service Technical Handbook 11*. Soil Conservation Service of New South Wales, Sydney.

Roth CH. 1992. Soil sealing and crusting in tropical South America. *Soil Crusting*, ME Summer and BA Stewart (eds.). Lewis Publishers, Boca Raton, FL, pp. 267–300.

Ruhe RV. 1959. Stone lines in soils. *Soil Science* 87: 223–231.

Ruiz HA, GB Ferreira and JBM Pereira. 2003. Estimativa da capacidade de campo de Latossolos e Neossolos Quartzarênicos pela determinação do equivalente de umidade. *Revista Brasileira da Ciência do Solo* 27: 389–393.

Sá JCM. 2004. Adubacão fosfatada no sistema plantío direto. *Simpósio Sobre Fósforo na Agricultura Brasileira*, RS Abdalla and NT Yamada (eds.). POTAFOS, Piracicaba, pp. 201–222.

Sá JCDM, CC Cerri, WA Dick, R Lal, SPV Filho, MC Piccolo and BE Feigl. 2001. Organic matter dynamics and carbon sequestration rates for a tillage chronosequence in a Brazilian Oxisol. *Soil Science Society of America Journal* 65: 1486–1499.

Sanchez PA. 1973. Puddling tropical rice soils. II. Effects of water losses. *Soil Science* 115: 303–308.

1995. Science in agroforestry. *Agroforestry Systems* 30: 5–55.

2015. En route to plentiful food production in Africa. *Nature Plants* 1: 1–4.

Sharma ML and G Uehara. 1968. Influence of soil structure on water relations in low humic Latosols. I. Water retention. II. Water movement. *Soil Science Society of America Proceedings* 32: 765–774.

Sharma PD, JK Ladha and L Bhushan. 2003. Soil physical effects of puddling in rice–wheat cropping systems. *ASA Special Publication* 65: 97–113.

Sidle RC, AD Ziegler, JN Negishi, AR Nik, R Siew and F Turkelboom. 2006. Erosion processes in steep terrain: Truths, myths, and uncertainties related to forest management in Southeast Asia. *Forest Ecology and Management* 224: 199–225.

Siebert SF and JM Belsky. 1990. Bench terracing in the Kerinci Uplands of Sumatra, Indonesia. *Journal of Soil and Water Conservation* 45: 559–562.

Silva VR, DJ Reinert and JM Reichert. 2000. Densidade do solo, atributos químicos e sistema radicular do milho afetados pelo pastejo e manejo de solo. *Revista Brasileira da Ciência do Solo* 24: 191–199.

Siriri D and T Raussen. 2003. The agronomic and economic potential of tree fallows on scoured terrace benches in the humid highlands of southwestern Uganda. *Agriculture, Ecosystems and Environment* 95: 359–369.

Six J, ET Elliott, and K Paustian. 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. *Soil Science Society of America Journal* 63: 1350–1358.

2000a. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry* 32: 2099–2103.

Six J, K Paustian, ET Elliott and C Combrink. 2000b. Soil structure and organic matter. I. Distribution of aggregate-size classes and aggregate-associated carbon. *Soil Science Society of America Journal* 64: 681–689.

Six J, P Callewaert, S Lenders, S De Gryze, SJ Morris, EG Gregorich, E A Paul and K Paustian. 2002a. Measuring and understanding carbon storage in afforested soils by physical fractionation. *Soil Science Society of America Journal* 66: 1981–1987.

Six J, RT Conant, EA Paul and K Paustian. 2002b. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil* 241: 155–176.

Six J, C Feller, K Denef, SM Ogle, JCDM Sá and A Albrecht. 2002c. Soil organic matter, biota and aggregation in temperate and tropical soils. Effects of no-tillage. *Agronomie* 22: 755–775.

Soane BD. 1986. Process of soil compaction under vehicular traffic and means of alleviating it. *Land Clearing and Development in the Tropics*, R Lal, PA Sanchez and RW Cummings Jr (eds.). Balkema, Leiden, pp. 265–283.

Soil Survey Staff. 1970. *Soil Taxonomy*. Natural Resources Conservation Service, United States Department of Agriculture, Washington, DC.

Suárez de Castro F and A Rodríguez. 1955. *Pérdidas por Erosión de Elementos Nutritivos Bajo Diferentes Cubiertas Vegetales y con Varias Prácticas de Conservación de Suelos. Boletín Técnico 14*. Federación Nacional de Cafeteros, Chinchiná.

1958. *Estudio en Lisímetros Monolíticos del Movimiento del Agua en el Suelo. Boletín Técnico 19*. Federación Nacional de Cafeteros, Chinchiná.

Subbian P, R Lal and V Akala. 2000. Long-term effects of cropping systems and fertilizers on soil physical properties. *Journal of Sustainable Agriculture* 16: 89–100.

Swindale LD. 1964. The properties of soils derived from volcanic ash. *FAO World Soil Resources Report* 14: 82–87.

1969. Properties of soils derived from volcanic ash. *Panel on Soils Derived from Volcanic Ash in Latin America*, Inter-American Institute of Agricultural Sciences, Turrialba, pp. B10.1–B10.8.

Syers JK, FWT Penning de Vries and P Nyamudeza (eds.). 2001. *The Sustainable Management of Vertisols*. CABI Publishing, Wallingford.

Tiffen M, M Mortimore and F Gichuki. 1994. *More People, Less Erosion. Environmental Recovery in Kenya*. African Centre for Technology Studies (ACTS) Press, Nairobi.

Tomasella J and MG Hodnett. 1998. Estimating soil water retention characteristics from limited data in Brazilian Amazonia. *Soil Science* 163: 190–202.

Tran LT, MA Ridgely, MA Nearing, L Duckstein and R Sutherland. 2001. Using fuzzy logic-based modeling to improve the performance of the revised Universal Soil Loss Equation (USLE). *The Global Farm 10th International Soil Conservation Organization Meeting*, DE Stott, RH Mohtar and GC Steinhardt (eds.). Purdue University, West Lafayette, IN, pp. 919–923.

Triomphe B and G Sain. 2004. Mucuna use by hillside farmers of northern Honduras. *Green Manures/Cover Crop Systems of Smallholder Farmers*, M Eilittä, J Mureithi and R Derpsch (eds.). Springer Nature, Philadelphia, PA, pp. 65–97.

Uehara G, KW Flach and GD Sherman. 1962. Genesis and micromorphology of certain structural soil types in Hawaiian latosols and their significance to agricultural practices. *Transactions of Joint Meeting of Commissions IV and V*, International Society of Soil Science, Wellington, pp. 264–270.

Usman H. 1994. Cattle trampling and soil compaction effects on soil properties of a northeastern Nigerian sandy loam. *Arid Land Research and Management* 8: 69–75.

Valentin C and LM Bresson. 1992. Morphology, genesis and classification of surface crusts in loamy and sandy soils. *Geoderma* 55: 225–245.

Valentin C, JL Rajot and D Mitja. 2004. Responses of soil crusting, runoff and erosion to fallowing in the sub-humid and semi-arid regions of West Africa. *Agriculture, Ecosystems and Environment* 104: 287–302.

van den Berg M, E Klamtb, LP van Reeuwijkc and WG Sombroek. 1997. Pedotransfer functions for the estimation of moisture retention characteristics of Ferralsols and related soils. *Geoderma* 78: 161–180.

Vanlauwe B, J Wendt, KE Giller, M Corbeels, B Gerard and C Nolte. 2014. A fourth principle is required to define conservation agriculture in sub-Saharan Africa: The appropriate use of fertilizer to enhance crop productivity. *Field Crops Research* 155: 10–13.

van Roode M. 2000. *The Effects of Vegetative Barrier Strips on Surface Runoff and Soil Erosion in Machakos, Kenya*. PhD Thesis, Universiteit Utrecht, Utrecht.

Wade MK and PA Sanchez. 1983. Mulching and green manure applications for continuous crop production in the Amazon Basin. *Agronomy Journal* 75: 39–45.

Walle RJ and BG Sims. 1999. Fertility gradients in naturally formed terraces on Honduran hillside farms. *Agronomy Journal* 91: 350–353.

Weil RR. 2011. *Using Simple Quantitative and Qualitative Field Tests to Diagnose Soil Limitations. ASA, CSSA and SSSA Annual Meetings October 16–19*. ASA, San Antonio, TX. See http://a-c-s.confex.com/crops/2011am/webprogram/Paper66974.html.

Willcocks TJ. 1981. Tillage of clod-forming sandy loam soils in the semi-arid climate of Botswana. *Soil and Tillage Research* 1: 323–350.

Williams JR and KG Renard. 1985. Assessment of soil erosion and crop productivity with process models. *Soil Erosion and Crop Productivity*, RF Follet and BA Stewart (eds.). American Society of Agronomy, Madison, WI, p. 67.

Wischmeier WH, DD Smith and RE Ukland. 1958. Evaluation of factors in the soil loss equation. *Agricultural Engineering* 39: 458.

Wischmeier WH and DD Smith. 1978. *Predicting Rainfall Erosion Losses: A Guide to Conservation Planning. Agricultural Handbook*. USDA, Washington DC.

Wolf JM. 1975. Soil–water relations in Oxisols of Puerto Rico and Brazil. *Soil Management in Tropical Latin America*, E Bornemisza and A Alvarado (eds.). North Carolina State University, Raleigh, NC, pp. 145–154.

Wolf JM and M Drosdoff. 1974. *Soil–Water Studies on Oxisols and Ultisols of Puerto Rico. Agronomy Mimeo 74–22*. Departments of Agronomy and Agricultural Engineering, Cornell University, Ithaca, NY.

World Bank. 2012. *Climate Smart Agriculture: A Call to Action*. World Bank Group, Washington, DC.

Yoder RE. 1936. A direct method of aggregate analysis of soils and a study of the physical nature of soil erosion losses. *Journal of American Society of Agronomy* 20: 337–351.

Young A. 1989. *Agroforestry for Soil Conservation*. CABI Publishing, Wallingford.

Ziegler AD and TW Giambelluca. 1997. Importance of rural road as source areas for runoff in mountainous areas of Northern Thailand. *Journal of Hydrology* 196: 204–229.