DEFORESTATION AND LAND USE: CHANGES IN PHYSICAL AND BIOLOGICAL SOIL PROPERTIES IN RELATION TO SUSTAINABILITY.

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Abstract

Clearing of tropical rainforest for agricultural or silvicultural purposes largely contributes to the decline in land area under undisturbed virgin forest. The development of more sustainable land use systems, allowing a prolonged economically viable production on the currently cultivated land, may contribute to reducing the pressure on the remaining forest reserves. The rapid decline in productivity of recently cleared land due to soil degradation, however, hampers the establishment of such production systems.

It is well known that the chemical soil fertility rapidly declines after removal of the forest cover, since the tight nutrient cycling which provided for the high biomass production of the forest, is interrupted. In contrast, hardly any attention has been paid to the decline in physical condition of the soil, although degeneration of the soil structure may strongly limit root penetration and root functioning in the soil, and may also increase losses of fertile soil through erosion. As soil faunal activity is a major structure forming and stabilizing factors in the soil, soil fauna are crucial for the establishment and/or maintenance of a physical soil condition favourable for plant growth.

Deforestation may affect the soil structure by the impact of various clearing operations (use of heavy machinery, burning of debris, removing stumps, etc.), by the more intense exposure of the soil to weather influences and by the change in quality and quantity of organic matter input. The subsequent land use determines whether the soil is offered an opportunity to regenerate or whether further stress is exerted on the soil. This study provides a literature survey dealing with the decline in soil physical conditions due to various land clearing and subsequent land use practices. This decline is brought in relation with changes in soil faunal populations and soil faunal activity. The potential to slow down or reverse the soil degradation by manipulation of soil fauna through providing favourable microclimatic conditions, increasing food supply and/or introducing new species is also investigated.

1. Introduction

The deforestation of tropical rainforests has attracted worldwide attention during the last decade. Although people living in or near the forests have always used these for collecting fruits and other foodstuffs, clearing small plots for agricultural purposes, chopping (small) trees for timber to build houses or taking branches as fuelwood, the scale and speed at which the current deforestation proceeds poses a serious threat to the existence of tropical rainforests. Furthermore, the reduced biomass production through clearing of the woods and the rapid turnover of organic matter resulting from burning of trees or from microbial or soil faunal decomposition of soil organic matter leads to a considerable increase in net carbondioxide production, thus contributing to global temperature changes (Palm et al., 1986).

Although estimates of the rate of forest clearing vary considerably and are rather unreliable (see review by Lal, 1987), most scientists do agree on the urgency of forest conservation measures and of an internationally coordinated policy on the exploitation of the tropical rainforests. The principal reasons for the deforestation can be grouped as (i) tradition/historic, (ii) economic and (iii) socio-political (Table 1).

Table 1: Principal causes of forest conversion (Lal, 1987)

Causes of deforestation		
Tradition/historic	Economic	Socio-political
1. Shifting cultivation	1. Agriculture	1. Strategic
2. Fuel wood	2. Ranching	2. Population migration
3. Harvesting forest products	3. Plantation crops	
	4. Timber and commercial wood	
	5. Urbanization	
	6. Infrastructure	

For centuries farmers have cut down pieces of forest ("slash and burn") and used it for crop production until the productivity had declined to an unacceptably low level because of weed problems or decline in soil fertility. Another piece of forest was then brought under cultivation and the former plot was left to regrowth of forest. This system of shifting cultivation is sustainable as long as the abandoned plots are left fallow for a sufficiently long period, before being brought under cultivation again. Nowadays, however, in many areas the pressure on the land has increased to such an extent that fallow periods are shortened or completely abandoned. Also marginal lands are being cleared which can hardly support agricultural activity. Degradation of the land, characterized by poor physical, chemical and biological soil conditions, is widespread and - in contrast with the situation under shifting cultivation - often of a permanent character.

With the development of heavy equipment mounted on crawler tracks and attachments specifically designed to facilitate the removal of vegetation, the scale of forest clearing has increased from simple hand cutting with a knife or chainsaw to large-scale mechanical operations. A major drawback of the use of such heavy machinery is the severe direct disturbance of the soil. If the land is intended to be used for urbanization or for infra-structural works, this is not necessarily problematic. If, however, the planned land use is agricultural or silvicultural, then it is of utmost importance not to cause any damage to the soil which can endanger its productive potential. For a land developer, not responsible for subsequent land management, it may be attractive to go for the short term benefit of a quick and easy tree felling, but the use of heavy machinery bears in itself the risk that once the land has been cleared it has become largely unsuitable for plant production. The post-clearing costs of reduced productivity or of inputs (chemicals or labour) for soil restoration, then are borne by the new land users. Small farmers, often belonging to the poorest class of society, cannot afford such inputs and, thus, are forced to take the land as it is in its degraded state.

Even if the deforestation operation itself has been done with the greatest care, drastic changes in soil conditions compared with the forested situation are inevitable. Removal of the forest cover results in totally different microclimatic conditions above and in the soil, a different soil water balance and a strongly reduced input of organic matter. The subsequent land use after clearing determines whether the soil may partially recover or whether further disturbance of the soil occurs. In case of agricultural use of cleared land, common practice in the past used to be to cultivate the land until it was exhausted, whereafter it was abandoned and a new piece of forest was cleared. Nowadays, the high demand for land makes it often impossible for a farmer to move to another plot. Moreover, in view of the quickly declining tropical forest reserves such a type of land use has become environmentally unacceptable. It is even questionable whether cutting down tropical forest in the long run can solve the problem of land demand for food sufficiency, if population growth continues at the current rate. Moreover, if equity of distribution of suitable land is taken into account, it can hardly be foreseen that there will be enough land to satisfy the demand. Ensuring that productivity of forest-derived agricultural land is maintained at levels enabling the farmer's family to feed themselves for a prolonged period, seems the only way to prevent further land clearing for agricultural purposes.

In case of silvicultural use of cleared land, soil degradation will lead to a poor reestablishment of secondary forest and thus to a low timber production level per unit land area. This will make it more attractive for a timber company to clear virgin forest, instead of attempting to establish long-term productive secondary forest. Also, the slow regrowth makes the soil to be poorly protected from rain for a relatively prolonged period, thus enhancing the risk of loss of soil material through erosion.

Therefore, if we do not want to lose all the tropical forest reserves, a more responsible use of current or future cultivated land is essential. Degeneration of the physical soil condition may largely reduce the potential of the land to sustain plant growth and thus endangers the establishment of sustainable land use systems. However, very little is known about the exact nature of the changes occurring in the soil during deforestation and subsequent land use and of the processes involved. This information is essential for the development of more sustainable land use systems, which is a prerequisite for the protection of the remaining tropical forests. This study deals with two little understood and causally related key factors, involved in the chain of processes leading to soil degradation following deforestation: changes in soil structure and soil physical properties, and changes in burrowing soil meso- and macrofauna. Such changes have to be studied in comparison with the undisturbed forest. The objective of this study is to determine which changes in physical and biological soil properties occur during deforestation and subsequent land use and to indicate what the consequences of such changes are for the development of sustainable production systems.

2. Soil properties under undisturbed rain forest

Tropical soils vary tremendously - often even within quite short distances - in physical and chemical characteristics, depending on parent material, age, climate, altitude, topography and biological factors. Yet, some degree of generalization about forest soils can be made.

Ignoring recent volcanic soils and recent alluvia, the soils in tropical rainforests are usually very old, often reaching back as far as the Tertiary period. The upper meters may have been weathered to leave chemically poor residues of sesquioxides (Al_2O_3, Fe_2O_3), kaolinite and quartz. Most of these soils, therefore, presently have a low natural fertility. Nutrients are contained largely in the phytomass of the virgin forest and in the biota and organic matter in the soil.

Although the organic matter input to the soil through the supply of litter or through dead roots usually is high, it generally decays quickly. As a consequence, a thick organic surface layer ("forest floor"), typical for many poor acidic soils of temperate and boreal forests, is generally lacking in tropical forests. Due to the intense burrowing activity of especially earthworms, termites and ants, organic matter is profoundly mixed through the soil, leading to a stable soil structure, which is close to ideal for root growth over a considerable depth (Emerson, 1991). The soil aggregates are water-stable, the soil has a low bulk density and the porosity is high and is formed by pores covering the full range of very small intra-aggregate pores to large interaggregate pores, many of which are continuous in depth.

As a result, soils under undisturbed forests have a high infiltration capacity, reducing runoff and erosion, while at the same time combine a high soil water retention with optimal soil aeration. In this way conditions are favourable to root growth, and thus for water and nutrient uptake. Efficient nutrient uptake by plant roots, often concentrated near the soil surface, combined with nutrient storage in soil organic matter with cation exchange sites and in the decomposer food web help to minimize nutrient leaching losses in spite of often high rates of water percolation (Jordan, 1985). As a result nutrient cycling is very tight, and a large total biomass can be maintained even if soils have lost most or all of their weatherable minerals.

3. Importance of soil fauna for soil physical properties

Soil animals play a crucial role in creating and maintaining a soil with favourable physical conditions, in which plant roots can easily penetrate, absorb water and exchanges gases (O_2, CO_2). This role is associated with the decomposition of dead organic matter, used by the animals as food (Verhoef & Brussaard, 1990). The building up of soil structure by soil fauna occurs by disturbing the solid soil matrix through mixing of soil particles, glueing them together to form aggregates and creating pores of all kinds of sizes and shapes. Lee & Foster (1991) mention the following soil faunal activities affecting soil structure:

- burrowing and excavation in search for food or for construction of living spaces or storage chambers;
- active transport of excavated or ingested soil material and its deposition on the soil surface or in voids within the soil;
- ingestion of soil material, often preferentially selecting plant litter or animal tissue;
- use of excreta, mucus or salivary secretions to line burrows or galleries or as adhesives to make construction materials;

- collection of plant litter, animal dung, carrion, etc. from the soil surface and its incorporation into the soil with or without prior digestion.

The basic framework of the structure is created by the soil macrofauna (earthworms, diplopods, beetles, etc.) and certain mesofauna as ants and termites, which are likely to be major regulators of soil organic matter dynamics by mixing the organic matter through the soil and transporting soil particles from the subsoil to the surface. The remaining mesofauna (springtails, mites, enchytraeids) are of less importance for the transport of soil particles, but play a central role in the formation of the soil microstructure by producing faecal pellets and all kinds of glueing substances during the decomposition of organic matter. The soil disturbing effect of microfauna is too small to directly affect soil structure.

A study of the role of soil fauna in creating a soil with favourable physical conditions should, therefore, in the first place focus on the macrofauna, ants and termites. As one of the aims of this study is to indicate the role of soil fauna in maintaining soil physical conditions after clearing of tropical rainforest, emphasis will be put on changes in soil faunal populations following deforestation. No attempt is made to fully review the voluminous literature existing on certain aspects (esp. concerning earthworms) of the relation between soil fauna and soil structure (see e.g. Lee, 1985; Lee & Foster, 1991). The following is restricted to soils of the (humid) tropics.

Earthworms

In the soil of tropical rainforest, earthworms usually are the most important element of the macrofauna. Also in tropical savannas they are often found in large numbers. However, their population densities may strongly vary among locations and in time, which is probably related to variations in quality and quantity of organic matter, but also the differences in soil water conditions. This is shown by data of Ghuman & Lal (1987) who found the earthworm density in a forest soil during the dry season to be only a small fraction (1-10%) of that during the rainy season. Lavelle (1983), comparing earthworm populations in various savanna sites, reported a linear relationship between the amount of mean annual rainfall and the number of earthworms.

Following Bouché (1971) and Lavelle (1981), earthworms are classified in three major ecological categories: (i) surface dwelling *epigeic* species, feeding on litter; (ii) soil dwelling *endogeic* species, feeding on soil organic matter or roots; and (iii) *anecic* species, which live in the soil but forage for litter at the soil surface. While feeding, earthworms ingest organic matter and (in case of geophagous worms) soil particles and deposit their faeces as casts at the soil surface or within the soil. Estimates on the amount of surface casts by tropical earthworms vary enormously: Anderson (1988) reported values in literature ranging from about 40 $t.ha^{-1}.yr^{-1}$ to a high value of 1200 $t.ha^{-1}.yr^{-1}$. This variation is not only related to species, but also to the type of organic matter ingested by the worms (Martin, 1982; Lavelle et al., 1989). Nye (1955) reported for a tropical forest soil that almost 100% of top few centimetres of the soil immediately beneath the litter layer existed of earthworm casts. Although less well documented than surface cast production, there is good reason to suppose that even more casting occurs belowground. Lavelle (1988) estimated for various earthworm species from Ivory Coastal savannas that only between 1.7 and 16% of the casting occurred aboveground. Graff (1971) estimated that belowground casting resulted in a yearly turnover of up to 25% of the total A_h-horizon.

Cast production is one of the major structure forming processes in many soils, creating a highly favourable physico-chemical environment for plant root growth. Many studies have shown that earthworm-worked soils have a lower bulk density, a higher fraction of water-stable aggregates, a higher porosity and better water retention and infiltration capacities than soils without earthworms (see reviews by Lee (1985) and Lal (1987)).

A very important aspect of earthworms is their effect on organic matter decomposition. According to Lal (1988) it is debatable whether earthworms have a favourable effect on the organic matter content of a soil or whether they merely thrive in the more fertile soils. However, Martin (1991) showed that under laboratory conditions the carbon mineralisation rate in casts of the tropical geophagous earthworm *Millsonia anomala* was 4 times lower than in control soil. This may indicate that under field conditions the organic matter in casts - i.e. the organic matter not digested by the worm - is better protected against rapid decomposition, a property which should be of the highest importance for maintaining soil fertility after clearing of a forest.

Termites

Termites are particularly important under arid or semi-arid conditions, where they have a stronger influence on soil properties than earthworms (Lal, 1988). They are most commonly found in parts of Africa and Asia, particularly India. Under tropical rainforest, they are of less importance and are mainly active during the dry season. The shift to a hotter and drier soil microclimate after deforestation, however, makes conditions more favourable to termites. As far as agricultural aspects of termite activity are concerned, attention has been mainly paid to the damage they cause to crops, both in field and storage, as well as to wooden structures, but little has been done to investigate the contribution of termites to the formation and maintenance of soil structure (Kooyman & Onck, 1987a).

The most prominently visible result of termite activity is formed by the elevated nests of the mound-building species. For the construction of these mounds termites dig down to the subsoil and bring soil particles to the surface. Termites commonly increase the clay content of the topsoil by preferential upward transport of fine soil particles. Pomeroy (1976), however, found termite mounds in a soil of high clay content to have a higher proportion of sand than the surrounding soil. Apart from this upward transport, soil particles are also transported downward or horizontally, as for instance seen from abandoned tunnels and nest chambers in the subsoil being backfilled with topsoil material (Wielemaker, 1984; Kooyman & Onck, 1987a). Termite activity, therefore, may lead to an intense mixing and homogenization of soil layers.

Most termite species consume dead organic matter. Those which feed on wood and litter often build subterranean chambers (fungus combs), in which they grow fungi to help digesting the lignin and cellulose. By bringing organic matter to these fungus combs, termites remove a large fraction of the litter from the soil surface. Estimates vary from 24% of the annual litter production from a primary woodland (Collins, 1981) to 30-90% of the litter from arable land (Kooyman & Onck, 1987a).

An important structure forming element in termite-worked soils is formed by pellets, created by cementing together clay particles with saliva and/or faecal material. The shape and composition of pellets vary with termite species and with oral or faecal origin of the pellets (Wielemaker, 1984). In creating a network of feeding galleries and channels and backfilling these with loosely arranged pellets, termites strongly affect soil structure and soil porosity of a much larger surface area than that covered by the mound itself. In areas with high termite activity pellets can even make up a large part of the soil matrix.

Although soil porosity is increased by termite activity, the effect on water infiltration rate depends on the continuity and orientation of these pores and on their connection to the soil surface. Termite channels below a mound are mostly going downwards, but in the rest of the soil they are more horizontally oriented (Kooyman & Onck, 1987a). Infiltration may be hampered by the deposition of fine clayey material from the subsoil on the soil surface, blocking pores.

The porosity of termite mounds often is very low due to the fine soil texture and the high grade of compaction, leading to a low water infiltration capacity. During heavy rainstorms horizontal surface flow of water may occur, resulting in erosion, thus affecting the texture of the neighbouring topsoil. Since the total surface area of the mounds is small, this aspect of increased erosion is only of local importance. On a time scale of centuries, however, it can have a significant influence on soil formation and soil texture (Wood, 1988).

Ants

There is considerably less emphasis in literature on the role of ants in soil formation than on the role of earthworms and termites, although e.g. Alvarado et al. (1981) state that leaf-cutter ants may be of major importance in soil development and genesis of Costa Rican Dystrandepts. Ants seem to play a major role in the colonization of recent soil deposits, such as flood planes and lacustrine deposits, on which they are one of the first animal species to settle (Kevan, 1962). Ants are particularly important in South America.

Depending on ant species, nests can be subterranean, consisting of a large number of interconnected channels and chambers with only a small opening to the soil surface, or aboveground, in which case mounds are build. While making their nests, ants dig down to the subsoil and transport soil particles to the soil surface. Nye (1955) observed that ants mostly used soil particles from the top 30 cm of the soil and that they preferentially selected coarse textured material for nest building. Data of other authors, however, suggest a preference for smaller particles (Alvarado et al., 1981).

Leaf-cutter ants may strip aboveground vegetation and incorporate the organic matter (leaves, flowers) into the soil, e.g. in fungal chambers. Alvarado et al. (1981) found that plants had a greater rooting depth in ant-disturbed profiles than in undisturbed ones, which, according to the authors, might be related to the higher organic matter content of subsoil layers through organic matter incorporation by ants.

The effect on soil physical properties of this digging and transporting activity are not well established, but based on the few literature reports available on this subject (Alvarado et al., 1981; Lal, 1987) one may expect a low soil bulk density and favourable water retention and transmission characteristics in ant-worked soil. On the other hand, since subterranean ant nests only have a few small exits to the soil surface, the effect on water transmission of the utmost toplayer may be small.

4. Steps in forest clearing

The land clearing methods currently used in tropical rainforest vary from the one extreme of labour intensive clearing by hand with only the help of simple tools like knives or machetes, to the other extreme of using capital intensive heavy machinery. Between these two a whole array of clearing methods exists, varying in labour, capital and equipment input. The question which method will be used depends on (i) general factors, like economic, legal or social considerations, and (ii) site specific factors, like climate, soil conditions, topography, type and density of vegetation, time frame and future use of the cleared plot (Ross & Donovan, 1986).

In traditional agriculture, based on shifting cultivation, often not the complete plot is cleared, but only some of the trees are removed selectively, leaving the others as protection against sun, rain or wind. Trees are felled with hand tools such as knifes, machetes or axes. Stumps are usually not removed to ensure a quick regrowth after having abandoned the plot. The felled trees are burned at the spot, liberating the nutrients stored in the wood. Crops are planted in between the remaining trees, preferably on previous burning sites where ash is concentrated.

As population pressure increases and so does the demand for land, more and more farmers are forced to settle. The selective removal of trees is then substituted by a total clearing of the plot, followed by burning of the felled trees. If clearing is not urgent, slow methods like ring barking or tree poisoning by chemicals, followed by hand clearing can be utilized (see Lal, 1986). Otherwise (semi-)mechanical methods are used.

The meaning of the terms semi-mechanical and mechanical clearing method is not strictly defined and depends on the user. The former indicates all kinds of techniques which are intermediate between the most primitive hand clearing and the highly capital intensive use of heavy machinery, being called mechanical clearing. Semi-mechanical clearing methods are not extensively used, since small peasants mostly work by hand, while government operations are usually based on the use of heavy equipment. In some countries, however, there is an increasing awareness that it is attractive to replace these capital intensive methods by locally available labour, occasionally supported by machinery (e.g. chainsaws).

A large number of mechanical clearing techniques have been developed, all based on the use of bulldozers equipped with various attachments (e.g. straight blade, tree pusher, tree crusher, shear blade, two bulldozers pulling a chain). Most commonly used are the straight blade method, implying the simply pushing over of a tree, and the shear blade method, with which the trunk is cut at soil surface level and the stump left in the soil. Descriptions of various methods are given by Lal (1986a).

The mechanical clearing process comprises the following steps (Ataga et al., 1986; Ross & Donovan, 1986):

1. Underbrushing: removing of shrubs and other undergrowth.
2. Lining: indicating which trees to fell and in which sequence.
3. Clearing paths for the machines.
4. Felling of trees, often followed by removing stumps and large roots.
5. Removing valuable trees: carrying or pulling trees to the tracks.
6. Windrowing: to rake debris into long piles for burning.
7. First burn.
8. Cutting and repiling: to prepare for second burn.
9. Second burn.
10. Post-burning operations: filling holes, harrowing, loosening top soil.

Every step in this list involves a certain disturbance of the soil, be it compaction due to repeated trespassing, heating through the burn, or mixing of soil layers. The correspondence among all mechanical methods concerning the effect on soil condition, is that they cause a considerable damage to the soil due to the heavy weight of the machines and the dislocation of soil particles. In the following paragraphs this damage will be described in more detail.

5. The effect of deforestation and subsequent land use on soil physical properties

Various studies have been done on the effect of land clearing method on soil physical properties, esp. bulk density. The effect of subsequent land use after clearing, however, has not received much attention. Furthermore, most studies reported in literature are of an observational nature, comparing soil conditions of land under various land uses with those under virgin or secondary forest. Since hardly ever detailed data on the past land clearing method and on the weather conditions during clearing (soil water condition!) are available, it is not possible to distinguish the effects of clearing from those of subsequent land use. To obtain these data experimental research is needed, specifically applying a range of treatments of land clearing methods and subsequent land uses. This type of work is largely lacking.

At IITA in Nigeria, Lal & Cummings (1979) and Lal (1981) deforested a plot using three clearing methods, followed by two tillage treatments and two levels of fertilizer application. During the following two years they compared the effect on some soil physical and chemical parameters and on maize grain yield. A more detailed study, involving different clearing methods and a number of post-clearing cropping systems was carried out at Okomu in Southern Nigeria by Ghuman et al. (1991) and Ghuman & Lal (1991). By far the most comprehensive long-term study was carried out by Alegre and colleagues in the low Amazon jungle of Yurimaguas, Peru. In a first phase they compared the effects on soil properties of mechanical bulldozer clearing versus slash/burn clearing (Seubert et al., 1977). In the second phase a study was initiated to reclaim land that was severely compacted by bulldozer clearing (Alegre et al., 1986b). In the last phase more comprehensive experiments were carried out to determine the rate of changes of selected physical properties during land conversion and to determine crop performance for various systems (Alegre & Cassel, 1986; Alegre et al., 1986a, 1990). At the same location, although not in the same plots, changes in soil faunal populations following deforestation and land use were determined by Lavelle & Pashanasi (1989).

In the following paragraphs degradation of the soil physical conditions due to land clearing and subsequent land use is described. Whenever possible, the effect of the land clearing method itself has been distinguished from the effect of subsequent land use.

5.1 Microclimatic soil conditions

The dense canopy structure of a rainforest provides an excellent protection of the forest soil to direct effects of wind, rain and sun. Clearing of the land leads to a partial or total removal of the forest cover and thus makes the soil to be exposed more intensively to weather extremes. The discontinuation of litter input to the soil and the rapid breakdown of existing surface organic matter after deforestation also contribute to a reduced shielding of the soil. This has marked influences on the microclimatic conditions in and just above the soil.

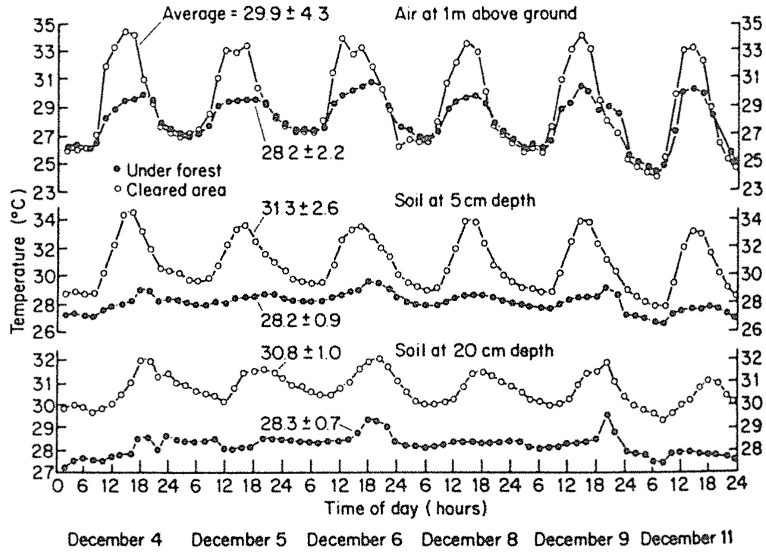

Figure 1: Soil and air temperatures under and outside (cleared area) the forest for six consecutive days during the season 1984/85 (Lal, 1987)

The removal of the forest cover leads to an increase in the amount of net radiation absorbed by the system due to changes in reflectivity, absorptivity and transmissivity (Lawson, 1986). Measurements during the dry month of December in Nigeria showed on average a 25-fold increase in solar radiation reaching the ground in cleared plots compared to the forest (Lal, 1987).

The energy input of the system through radiation may be used for heating up the soil (soil heat flux), for heating up the air above the soil (sensible heat flux) or for evapotranspiration (latent heat flux). Evapotranspiration from a forest usually is much higher than from other vegetation types due to the following factors (Lawson, 1986): (i) a larger surface roughness, leading to a higher degree of turbulent mixing and transport of water vapour; (ii) higher rate of water loss from the soil under relatively dry conditions due to the intensive root system, the greater volume of soil explored and the higher water retention of the forest soil; (iii) higher rainfall interception by the vegetation. The decrease in evapotranspiration after deforestation leads to a larger fraction of the incoming radiant energy to be expended into sensible and soil heat fluxes, thus heating up the soil and the air above it. Not only average daily temperatures are higher in the cleared plots, but also temperature fluctuations. From experiments at IITA in Nigeria, Lal (1987) reported forest clearing resulted in an increase in maximum temperature by 5 to 8 °C and a decrease in minimum temperature by 1 to 2 °C at 10, 50 and 100 cm above the ground surface. Greatest differences in air temperature between cleared and forested plot occurred at 1 m above the ground surface. Furthermore, maximum temperatures in a cleared plot may be attained earlier and last longer than under a forest cover (Figure 1).

The increase in air temperature after deforestation, the higher wind velocity over the plot and the reduction in water vapour input into the air through evapotranspiration result in a lower aerial relative humidity above cleared plots. Lawson et al. (1981) showed that differences in relative humidity between a cleared and a forested site were most pronounced for the minimum rather than maximum rh-values. Their data also clearly show the effect on the minimum relative humidity of forest canopy reestablishment after the onset of the rains (Figure 2).

Although total evapotranspiration from a cleared plot is much lower than from a forested plot, water loss from the soil surface through evaporation usually increases after removal of the forest cover. This is caused by the higher ambient temperatures and the lower minimum relative humidity, as related to the more direct exposure of the soil to sun and wind. Lawson et al. (1981) found that total evaporation from a forest soil during the period March to September was 794 mm, whereas for a cleared soil it had increased to 1409 mm. As a consequence, the toplayer of the soil in a cleared plot is much more prone to desiccation than under a forest.

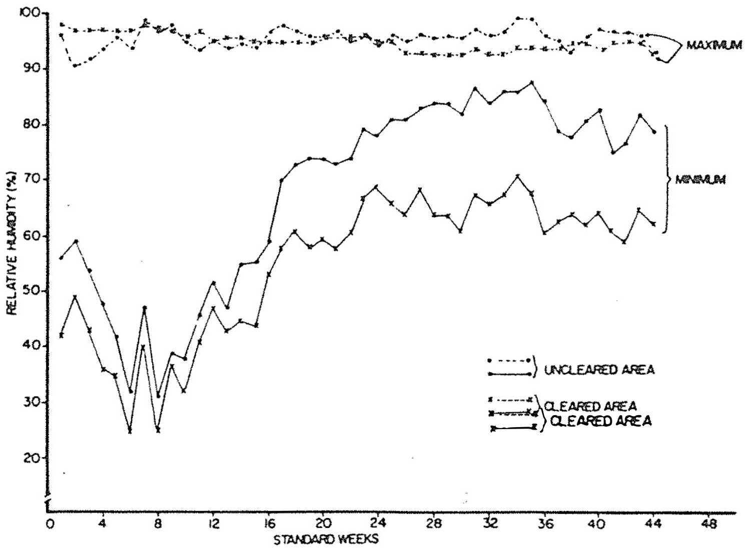

Figure 2: Comparative values of daytime minimum and maximum relative humidity in a forest and in a cleared area at IITA, Nigeria (Lawson et al., 1981)

5.2 Soil texture

5.2.1 Effect of land clearing

In an undisturbed situation soil texture is constant in a time span short enough to neglect weathering of minerals, unless import or export of soil particles occurs by erosion, flooding etc.. The clearing of the land in itself not necessarily changes this stable situation, if carried out carefully. In an experiment of Ghuman et al. (1991) on an Ultisol in Nigeria, neither manual clearing nor shear blade clearing led to a change in particle size distribution of the 0-10 and 10-20 cm layers. Similar results were found by Alegre et al. (1986a) for slash/burn, straight blade or shear blade clearing. The use of heavy equipment, however, can lead to a scraping off of (part of) the topsoil, which subsequently can be blown or washed away. Also the levelling of the land by harrowing leads to transferring soil particles from one place to another, as demonstrated by Moreau (1986), who described how the scouring and mixing of termite mounds, rich in clay, resulted in an increase of 3 to 5 percent in clay and silt content of the surface soil.

Vertical disturbance of soil texture by deforestation occurs with certain land clearing methods. For instance, the pulling out of trees with complete root systems can lead to excavations of 20 to 30 cm depth, which later on have to be filled with surface soil, thus mixing top- and subsoil. The same occurs when stumps and thick roots are removed after tree felling, in order to maximize the area of land available for cropping and to facilitate the working of the soil. This is also needed for a high-quality pasture without shrub and bush regrowth. Allan (1986) mentioned a depth of 30 cm from which all tree roots and stumps should be removed in order to change the plot into cultivable land.

A direct consequence of the removal of the forest cover is the exposure of the soil to forces of raindrop splashing, which may lead to dislocation of clay particles followed by migration from the topsoil to deeper layers (Table 2). De Boer (1972) hypothesized that dislocation of clay particles could be related to the increase in soil pH from the ash after burning.

Table 2: Textural composition of soil (%) as affected by deforestation (Mambani, 1986)

Horizon	Depth (cm)	Clay		Silt		Sand		(Clay+Silt)/Sand	
		Virgin forest	Cleared plot	Virgin forest	Cleared plot	Virgin forest	Cleared plot	Virgin forest	Cleared plot
A1	0-10	20	18	3	3	77	80	0.30	0.26
A12	10-27	20	20	2	2	78	78	0.28	0.28
A-B	27-49	23	28	3	2	74	69	0.35	0.43
B1	49-96	24	26	2	2	74	73	0.35	0.38
B2	96-176	20	26	4	2	76	72	0.32	0.39

5.2.2 Effect of land use after clearing

Cultivation of land always involves a certain degree of mixing of soil layers by digging, hoeing or ploughing. Since this is a common feature of any agriculture land use, no further attention is paid to it here.

Apart from soil tillage, the degree of soil exposure to weather determines whether changes in soil texture may occur during land use. When the soil is left largely uncovered during the rainy period, the beating effect of raindrops may lead to dislocation of clay from topsoil aggregates, followed by eluviation to deeper layers. Cunningham (1963) compared the change in textural properties of a Ochrosol (light sandy loam) after various degrees of exposure. It was observed that after three years of full exposure the coarse sand fraction of the 0-5 cm layer had increased, whereas the fine sand, silt and clay fraction had decreased (Table 3). For the layer 5-15 cm the opposite trend was observed, suggesting a partial eluviation of clay from the surface layer into a deeper layer.

After 4 years of cropping a newly cleared plot, Ghuman et al. (1991) found an increase in sand fraction of the topsoil with those crops (plantain and pasture) in which the soil was left bare during the first 2 years. For other crops, giving more protection to the soil by crop residues left in the field, no change was observed (cassava, oil palm, alley cropping and improved forestry).

The authors attributed this difference to clay eluviation following raindrop impact.

Table 3: Effect of degree of soil exposure on distribution of textural fractions (%) of the soil (Cunningham, 1963)

	0-5 cm layer			5-15 cm layer		
	coarse sand	fine sand	silt + clay	coarse sand	fine sand	silt + clay
shade	33.1	35.1	26.3	44.8	30.9	22.8
half exposure	35.0	34.6	27.6	42.8	33.5	22.5
full exposure	43.8	30.4	23.6	34.0	36.6	28.6

5.3 Soil structure

5.3.1 Effect of land clearing

A number of authors reported soil compaction after land clearing. It is, however, not always clear what exactly is meant by compaction, as this term is often used to indicate any change in soil structure. Strictly speaking compaction only refers to an increase in bulk density, but often no clear distinction is made between compaction and displacement of soil (Figure 3).

Hand clearing of a forest usually leads to only a slight increase in bulk density of the topsoil, since pressure exerted on the soil by man's weight is minimal (Table 4). If animals are used to drag the felled trees out of the forest, locally very high pressures are exerted on the soil, but since these are only of a short duration and hoof prints are very small the compacting effect will be limited. The dragging of the trees, however, can cause smearing of the soil, esp. when the soil is wet. Mambani (1986) manually deforested a plot on a Ferrasol by slash/burn and found an increase in mean bulk density from 1.19 to 1.49 $g.cm^{-3}$ in the top 10 cm, which the author attributed to the vertical stress due to falling of trees and rain drop impact. Unfortunately, data for deeper layers were lacking. Data from Alegre et al. (1986b) on a Typic Paleudult at Yurimaguas, Peru, showed that the compacting effect of slash/burn clearing was limited to the upper soil layer (0-15 cm). Ghuman et al. (1991) found that manual clearing resulted in a bulk density increase of an Ultisol from 1.07 to 1.22 $g.cm^{-3}$ for the upper 10 cm of the soil and from 1.17 to 1.30 $g.cm^{-3}$ for the 10-20 cm layer. No effect was observed in the 20-30 cm layer.

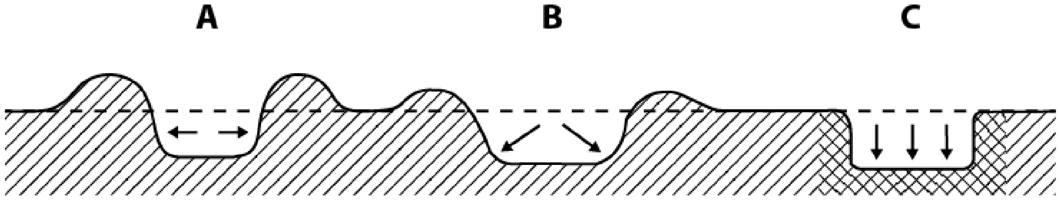

Figure 3: Three types of ruts created by the passage of a wheel or track. A: pure displacement; B: part compaction, part displacement; C: pure compaction (Abeels (1981), cited by Soane (1986))

The use of various types of bulldozers for land clearing causes the pressure exerted on the soil to increase 2- to 3-fold (Table 4). Although this is still considerably lower than the pressure from animal hoofs, the larger surface area of the wheel tracks makes the compaction have a much wider impact. Lal & Cummings (1979) observed a 10- to 20-fold increase in penetrometer resistance of the 0-4 cm layer of a mechanically cleared plot, compared with a 3- to 4-fold increase after hand clearing. Furthermore, the penetrometer resistance was about twice as high under the wheel tracks than on the rest of the plot.

Table 4: Weight and pressure range over the soil produced by various compacting agents (Toledo & Morales, 1979; cited by Toledo & Navas, 1986)

Compacting agent	Weight (t)	Pressure range on soil ($kg.cm^{-2}$)
Bulldozer (180 hp)	18.30	0.51 - 0.67
Bulldozer (270 hp)	28.10	0.68 - 0.95
Bulldozer (385 hp)	38.80	0.76 - 0.95
Tree crusher G-40 (575 hp)	45.00	1.00 - 1.03
Tree crusher G-60 (475 hp)	65.00	1.00 - 1.37
Horse	0.40	1.00 - 4.00
Cow	0.35	0.88 - 3.50
Man	0.07	0.23 - 0.47

An important difference with the effect of hand clearing is that the compacted layer from mechanical clearing extends to a much greater depth, whereas often the strongest compaction is not found at the soil surface, but at some depth. Janssen & Wienk (1990) showed that mechanically clearing of a dryland forest on a loamy soil in Surinam led to a considerable increase in bulk density down to at least 90 cm depth. The maximum increase (from circa 1.43 to 1.65 $g.cm^{-3}$) was found at a depth of circa 35 cm. Also from Surinam, Van der Weert & Mahesh (1972) reported for a sandy loam a maximum increase from 1.43 to 1.78 $g.cm^{-3}$ at a depth of 10-15 cm, whereas compaction extended down to circa 50 cm depth. In both situations hand clearing gave rise to only a slight superficial compaction.

Alegre et al. (1986a) compared slash/burn clearing on a Typic Paleudult in Peru with mechanical clearing by straight blade or by shear blade. All methods gave a significant increase in bulk density of the 0-15 cm layer, the straight blade causing the strongest compaction. Inter-replicate variation of the mechanically cleared plots, however, was so high that differences between treatments were not significant (Table 5). This variation may be a reflection of the existence of compressed tracks. In the 15-25 cm layer only the mechanical methods increased bulk density.

After a shear blade clearing operation on an Ultisol, Ghuman et al. (1991) found a bulk density increase for the top three 10-cm layers from, respectively, 1.07 to 1.31 $g.cm^{-3}$, 1.17 to 1.51 $g.cm^{-3}$ and 1.35 to 1.42 $g.cm^{-3}$. All these increases were bigger than with manual clearing.

During the deforestation operation soil aggregates may be destroyed by crushing. Alegre & Cassel (1986) found that slash/burn clearing did neither affect the mean aggregate diameter (Table 6) nor the distribution of soil aggregates among size classes. Mechanical clearing - esp. by straight blade - resulted in a shift towards smaller aggregates. Since aggregate stability is often directly related with organic carbon content, this parameter is worth considering in this context. Table 6 shows indeed a clear correlation between decreasing organic carbon content and decreasing aggregate size.

Table 5: Mean bulk density and sd (in parentheses) of the soil prior to and 14 weeks after land clearing, but before planting the first crop (Alegre et al., 1986a)

Time	Clearing method	0-15 cm depth		15-25 cm depth	
Before clearing		1.16	(0.09)	1.39	(0.08)
After clearing	slash/burn	1.27	(0.07)	1.37	(0.10)
	straight blade	1.42	(0.12)	1.49	(0.12)
	shear blade	1.28	(0.25)	1.50	(0.15)

If not all the trees from a certain parcel are felled, but only the best are taken out selectively for timber trade, trees have to be dragged to one of the access roads. In areas with a high groundwater table (or if the work is done in the rainy season) soil strength can be so low that tractors cannot use the same access road twice. Baltissen (1988) mentioned for a Costa Rican forest that 10-12 roads per ha were created for only removing a few trees. He estimated that this resulted in severe compaction of circa 10% of the land area, whereas another circa 10% was moderately damaged.

Very harmful to the soil structure is the skidding of wheels, occurring when the soil is wet or when a tree is not easily pushed over by the tractor. This may lead to smearing and total destruction of the topsoil structure. Also the dragging of trees out of the forest may lead to smearing the topsoil. A proper timing of the clearing operation, so that it is carried out in the dry season, therefore, is of greatest importance.

Table 6: Soil aggregate mean weight diameter (mm) and geometric mean diameter (mm), and soil organic carbon content (%) before and 3 months after land clearing (sd in parentheses; Alegre & Cassel, 1986)

	Mean weight diameter	Geometric mean diameter	Organic carbon content
Before clearing	0.484 (0.090)	0.556 (0.060)	1.04 (0.20)
Slash/burn	0.424 (0.098)	0.516 (0.068)	1.05 (0.10)
Shear blade	0.358 (0.073)	0.485 (0.042)	0.87 (0.20)
Straight blade	0.292 (0.063)	0.439 (0.037)	0.82 (0.17)

5.3.2 Effect of land use after clearing

Hartge & Ellies (1990) analyzed data of a number of plots under various land uses from 3 locations in south Chili, two on a Typic Dystrandept and one on a Andeptic Palehumult, and compared these with the land use history of each of these plots. They concluded that those plots which had been under agricultural use in the past or still were, had a state of compaction higher than could be expected on the basis of natural paedogenetic processes (for theoretical background see Hartge, 1986). This especially was the case for pastures, which soils had a compacted top layer and a relatively high consistency of soil structure (expressed as penetrometer resistance divided by porosity). Plots which had been reafforested had a more loosened soil, but still with a high consistency. A weak point in this kind of studies, however, is the reliability and completeness of the historical data. Important data which are invariably missing are the deforestation method and the soil disturbance involved (soil water condition!).

A bulk density increase with cropping time (up to 4 years) in the top 10 cm layer was observed by Ghuman et al. (1991) for all tested cropping systems in mechanically cleared plots, except for the (ungrazed!) pasture, in which the bulk density decreased (Table 7). For deeper layers no clear changes in time could be indicated, again with the exception of the pasture which also for this layer showed a decrease in bulk density. The different results for the pasture soil probably are related to the high organic matter input from roots and cut grass, stimulating soil fauna. As shown in paragraph 6, earthworm activity can be particularly high under pasture. In traditionally cleared plots bulk density decreased with time in the topsoil, probably also because of the high return of organic matter to the soil.

Table 7: Effect of land use system on soil bulk density at two depths after 2 and 4 years of cropping (sd in parentheses; Ghuman et al., 1991)

Land use	0-10 cm		10-20 cm	
	Before clearing			
	1.07 (0.11)		1.17 (0.09)	
	Manually cleared			
	2 yrs	*4 yrs*	*2 yrs*	*4 yrs*
Traditional cropping	1.20 (0.12)	1.07 (0.17)	1.25 (0.03)	1.22 (0.02)
	Shear blade cleared			
	2 yrs	*4 yrs*	*2 yrs*	*4 yrs*
Cassava based	1.15 (0.10)	1.24 (0.03)	1.44 (0.08)	1.42 (0.10)
Oil palm based	1.09 (0.08)	1.29 (0.03)	1.35 (0.08)	1.41 (0.10)
Alley cropping	1.11 (0.08)	1.28 (0.03)	1.40 (0.10)	1.53 (0.15)
Plantain	1.25 (0.06)	1.34 (0.08)	1.51 (0.11)	1.45 (0.14)
Pasture	1.34 (0.05)	1.21 (0.06)	1.41 (0.05)	1.30 (0.06)
Improved forestry	1.20 (0.07)	1.25 (0.10)	1.48 (0.06)	1.54 (0.09)

A series of studies on the effect of land use on soil structure were carried out by the Wageningen Agricultural University in cooperation with the Centro Agronomico Tropical de Investigacion y de Enseñanza (CATIE) on volcanic soils in Costa Rica. Baltissen (1988) found that the land clearing itself (done by hand or mechanically) resulted in a slight compaction of the top few cm of the soil, accompanied by a shift to an apedal (young Humitropept) or somewhat physicogenic (old Dystrandept) structure. Other soil characteristics, like porosity or consistency, were not altered. However, the structure of the Humitropept under circa 10 year old pasture or cacao had changed from porous granular crumb to dense, porous massive. Symptoms of water stagnation such as a grey colour and many red mottles were found in the layer just below the immediate topsoil. Under the same land use the Dystrandept also had become compacted, but never had turned as massive as the other one. The compaction could probably be ascribed to the use of heavy machinery during cultivation of the land, and (for the pasture) to trampling of the soil by cattle. Lansu (1988) found the topsoil structure of a Typic Dystropept increasingly degraded in the sequence forest - mixed cropping - pasture - maize; no differences were observed in the subsoil. She attributed these differences to the effect of external forces (rain, trampling by cattle) and especially to a reduced working of the soil by soil fauna. De Wolf (1988) compared bulk densities of a young Andept and an old Ultisol, both under forest and pasture of varying age. It was shown that the pasture soil on Ultisol had reached a higher degree of compaction than that on the Andept, and that the compaction of the Ultisol increased with period of land use as pasture. In contrast with these studies was a report of Spaans et al. (1989) who found no difference in bulk density of an old Tropohumult and a young Humitropept under, respectively, 3 and 35 year old pasture, compared to the soils under forest (although later measurements did show an increased bulk density; pers. comm. E. Veltkamp). Other symptoms of structure degradation, such as easy puddling and low saturated hydraulic conductivity, were most severe in the old soil, although this one was only very recently brought under cultivation. It was concluded from these studies that the most drastic changes in soil structure did not result from the act of deforestation itself, but from the subsequent land use. Older more weathered volcanic soils seem more susceptible to compaction and structural degradation than younger volcanic soils. Most damaging are those land use systems in which the soil is exposed to forces of rain drop splashing or trampling by cattle, or in which soil faunal activity is strongly reduced.

Table 8: Bulk density and penetrometer resistance (expressed as the logarithm of the cone index) of the soil 29 weeks after clearing, just prior to harvesting the first crop (sd in parentheses; Alegre et al., 1986a)

	0-15 cm depth			
	bulk density (g.cm^{-3})		Log$_{10}$(Cone index)	
Flat planted	1.30	(0.14)	2.685	(0.338)
Flat planted + fertilizer + lime	1.28	(0.13)	2.635	(0.324)
Bedding + fertilizer + lime	1.14	(0.13)	2.460	(0.358)
	15-25 cm depth			
	bulk density (g.cm^{-3})		Log$_{10}$(Cone index)	
Flat planted	1.47	(0.18)	2.763	(0.286)
Flat planted + fertilizer + lime	1.49	(0.13)	2.761	(0.289)
Bedding + fertilizer + lime	1.46	(0.13)	2.817	(0.302)

In contrast with this conclusion were the results of a very detailed experiment in Peru by Alegre and colleagues (Alegre & Cassel, 1986; Alegre et al., 1986 a+b). They found that the degrading effect of land clearing itself was much greater than the effect of subsequent land use. Shortly after deforestation a downward shift in the size of water stable soil aggregates and in mean aggregate diameter was observed for those plots which were mechanically cleared. Although the authors cited various reports in which it was found that cultivation and continuous cropping led to a reduction in aggregate stability (Gomes et al., 1978; Moreau, 1978), continuous cropping in this experiment did not cause further destruction of soil aggregates. Only a very slight increase in the relative contribution of the 0.1-0.25 mm fraction occurred. They also tested the effect of soil tillage as a way to cope with the increased soil bulk density after clearing. However, there were no differences in bulk density or penetrometer resistance between ploughed and unploughed plots at any time of the cultivation period. Bedding of the soil in stead of flat planting did reduce the bulk density and penetrometer resistance of the 0-15 cm layer after the first cropping cycle (Table 8). This might be due to a reduced compression by foot traffic from labourers during weeding, as they did not walk on the beds. In the 15-25 cm layer no differences were found. After the fifth cropping cycle differences between bedded and flat treatments had disappeared, and bulk density of all treatments had further increased.

5.4 Porosity, water retention and water infiltration

5.4.1 Effect of land clearing

The porosity of a soil is an important parameter for plant growth, as it determines the water and air balance of the soil and influences the ease of root penetration. A soil of favourable porosity contains a range of pore size classes that (i) ensure an easy uptake of water, exchange of gasses (O_2 and CO_2) and soil penetration by the roots, (ii) enable a rapid infiltration of rain water, so as to reduce the superficial flow causing erosion, and (iii) provide a suitable habitat to various soil animals (not forgetting that the fauna itself strongly affects the porosity).

The increase in bulk density of the soil often observed after deforestation will be accompanied by a compression or silting up of pores, fissures and voids, which may lead to a reduction in total porosity or a shift in pore size distribution towards smaller pores. The loss of aggregate stability causes a decline in the number of (larger) inter-aggregate pores and a relative increase in the number of (smaller) intra-aggregate pores. The drop in soil faunal activity (chapter 6) leads to an evolution from a soil with mainly biogenic porosity to one in which porosity is mainly of a physicogenic nature. The former is characterized by many very fine compound packing voids and biogenic pedofeatures such as channels and vughs which are to a large extent interconnected in both top- and subsoil. In the latter situation pore orientation has changed in a more horizontal direction, macropore continuity is interrupted, partly because of the removal of deep-rooted perennials, and planar voids dominate (Baltissen, 1988; Lansu, 1988).

In the topsoil a shift to smaller pores due to compression may be counteracted by a loss of fine soil particles due to eluviation of clay, resulting in an increased fraction of coarse soil particles and thus a higher contribution of large pores to total pore volume. In the subsoil, on the contrary, the illuviated clay may fill up interaggregate pores, further enhancing micropore formation. This process was clearly demonstrated by Mambani (1986), comparing soil properties of a cleared plot and a virgin rainforest on kaolinite dominated Ferrasols in Zaire. He reported a large and significant increase in bulk density of the topsoil due to clearing, but only a very small decrease in total porosity and a slight increase in macropore contribution to total porosity (Table 9). In deeper soil layers (40-60 cm) a large shift from macro- to micropores was found, however not accompanied by a significant bulk density increase. These changes could be explained from the topsoil compaction during clearing, in combination with migration of clay particles to deeper layers as shown by the decreased ratio of clay+silt to sand in the topsoil of the cleared plot and increased values in the subsoil.

Table 9: Total soil porosity (% of total volume) and pore size distribution (% of pore volume) at various depths in virgin forest and cleared plots (Mambani, 1986)

	Total soil porosity		Fissures and transmission pores		Storage pores		Residual pores	
Depth (cm)	Virgin forest	Cleared plots	Virgin forest	cleared plots	Virgin forest	Cleared plots	Virgin Forest	Cleared plots
0-20	51	49	62	63	30	29	9	8
20-40	46	46	56	60	32	31	12	9
40-60	42	42	47	26	40	48	13	26

A change in total porosity or in pore size distribution affects the water retention characteristics of the soil. Micropores remain water-filled until much lower (more negative) matric potentials than macropores, whereas macropores and voids are important for a rapid drainage after a shower. For coarse-textured soils, a change in soil water retention following forest clearing is also associated with the rapid decline in soil organic matter content. The amount of water released between the matric potential at field capacity (10 kPa or pF=2) and at wilting point (1500 kPa or pF=4.2) can be considered to approximate the amount of plant available water. Directly related to changes in water retention characteristics of the soil, are changes in soil aeration. As it are primarily the larger pores which are important for soil aeration, the shift to smaller pore sizes combined with a lower total porosity can have drastic negative consequences for the aeration of the soil.

On a sandy loam in Surinam, Van der Weert & Mahesh (1972) found the small increase in bulk density of the topsoil after hand clearing not being reflected in a decreased total porosity, but a clear shift was observed from macro- and, especially, mesopores towards micropores in the top 30 to 40 cm. Such an increase in micropore volume at the cost of macropore volume, while total porosity remains the same, will lead to a more gradual release of pore water with decreasing matric potential. At field capacity the soil will have a larger volumetric water content than in undisturbed conditions, as will also be the case at wilting point suction. Whether total amount of available water is affected depends on the relative changes in these two parameters. Mambani (1986) found that total pore volume had slightly decreased in the topsoil due to hand clearing, but this did not affect the amount of available water, since both water retention at field capacity and at wilting point were lowered comparably. In the subsoil the total porosity was not altered, but the shift to smaller pores led to a stronger increase in volumetric water content at field capacity than at wilting point and thus to a larger amount of available water.

In the experiment of Alegre and colleagues mentioned earlier (Alegre et al., 1986a; Alegre & Cassel, 1986) it was found that mechanical clearing - esp. by straight blade - resulted in a considerable soil compaction and in a shift towards smaller water stable aggregates. From this it can be deduced that there must have been a concomitant reduction in macropore volume, probably increasing micropore volume. For the straight blade treatment this increase in small pore fraction indeed is likely to have occurred, since both the top- and subsoil showed a higher soil water retention at water pressures < -2 kPa than the undisturbed forest soil. The strongly reduced water infiltration rate of the mechanically cleared soils - to values of circa 8% (shear blade) and 3% (straight blade) of the forest soil value - make it likely that not only pore distribution had changed, but total porosity had decreased also. The same picture was drawn by Van de Weert & Mahesh (1972) who found the strong compaction of the profile down to 80 cm depth after mechanically clearing being mirrored by a decrease in total porosity of the total profile and an almost complete non-existence of macropores in the top 20 cm and a strong reduction in the rest of the profile. Meso- and micropore volume had declined and increased, respectively, especially in the top 20 to 30 cm.

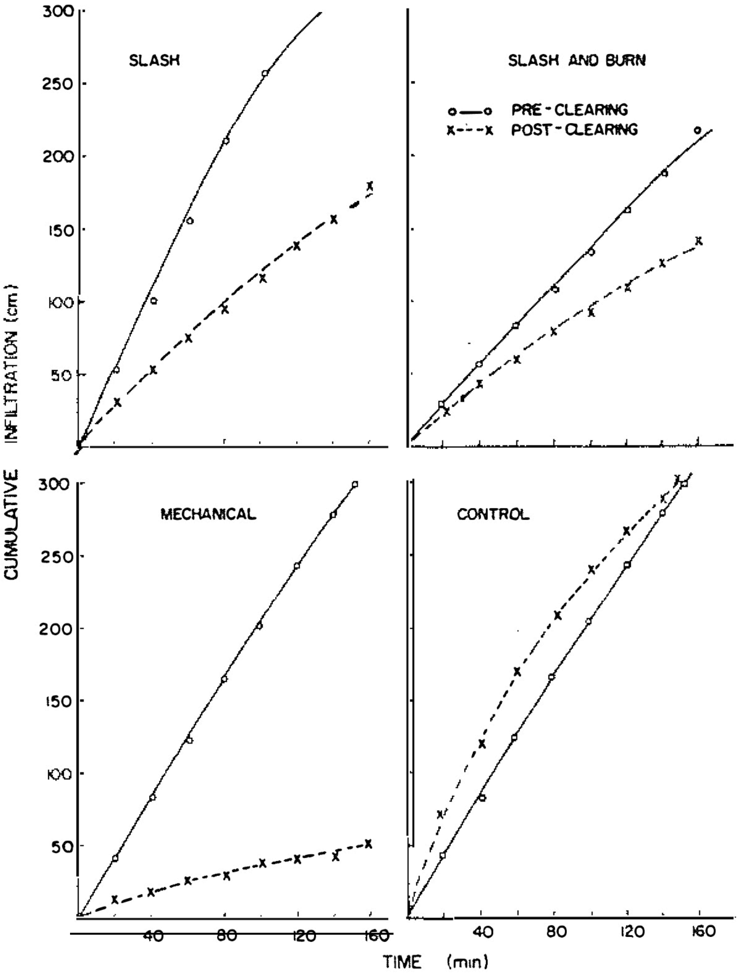

Figure 4: Effect of deforestation method on cumulative water infiltration rate (Lal & Cummings, 1979)

Lal & Cummings (1979) deforested plots on a Paleustalf using different clearing methods (slash, slash/burn, mechanical clearing). They found that both manual clearing methods resulted in only a slight decline in soil water retention at zero suction, whereas with mechanical clearing its value decreased from 0.35 $g.g^{-1}$ to 0.22 $g.g^{-1}$. This was attributed to a decreased porosity, mainly resulting from a reduction in macro-pore volume.

As a result of changes in total porosity and pore size distribution after deforestation, clear differences in water transmission characteristics of the soil after different clearing methods may also be expected. Seubert et al. (1977) found that, one month after clearing, cumulative water infiltration rate in a Typic Paleudult was 12 times higher on a slash/burn cleared plot than on a straight-blade cleared plot. In the experiment of Lal & Cummings (1979) in Nigeria, cumulative water infiltration rate was found to have decreased shortly after clearing by 45, 66 and 75% of the pre-clearing value in, respectively, the slash, slash/burn and mechanically cleared plots (Figure 4). Ghuman et al. (1991) found that the infiltration rate for manually and shear-blade cleared plots had decreased down to, respectively, 36 and 22% of the forest soil value. The inter-replicate variation, however, was too large to show a significant difference between the two methods.

5.4.2 Effect of land use after clearing

Reports on the effect of land use after forest clearing on soil porosity are scarce, as in most studies the effect due to cultivation cannot be separated from the effect of the clearing method. A study in Costa Rica by Lansu (1988) showed a decline in total porosity of the topsoil in the same land use sequence as was earlier mentioned for the increase in bulk density: forest (55% porosity) - mixed cropping (50%) - pasture (20%) - maize (circa 15%). The type of voids changed from mainly biogenic (forest) to mainly physicogenic (maize). From about the same field location, Spaans et al. (1989) reported that total pore volume under pasture on an old Tropohumult had not changed compared with the forest soils, but macropore (30-5000 µm) volume had decreased drastically in both the 5-15 cm and 20-30 cm layer. Within the group of macropores a shift to smaller pore size classes had occurred. Consequently, saturated hydraulic conductivity (K_{sat}) under pasture had decreased to 5% of its original forest value (see also Spaans et al., 1990). In a younger Humitropept, macroporosity was also lower under pasture, but K_{sat} was not affected.

From the earlier mentioned experiment of Alegre et al. (1986a) it appeared that continuous cropping led to a reduction in infiltration rate for the slash/burn treatment, but to an increase for the treatments which were mechanically cleared and subsequently ploughed. This may be explained from the fact that the former treatment had not suffered badly from the clearing itself, so any further cultivation could only lead to compaction. In contrast, Ghuman et al. (1991) found a strongly increased infiltration rate after 2 years cropping of a manually cleared plot, to values even much higher than in the forest control. This probably resulted from decomposition of old tree roots and subsequent pore formation. However, after 4 years the infiltration rate had decreased again, which the authors attribute to collapse of the old tree root channels and they mention to expect a further decrease down to values below that of the forest control (Figure 5).

Table 10: Effect of land clearing method and tillage on soil water retention ($cm^3.cm^{-3}$) for 0-10 cm soil depth (Lal, 1981)

Suction (bar)	Clearing method				Tillage method		
	Mechanical	Slash/burn	Slash	LSD (0.05)	No tillage	Ploughed	LSD (0.05)
0	34.0	36.8	37.3	6.9	38.2	34.5	3.9
0.1	14.8	15.2	15.4	3.9	16.8	13.5	2.4
0.3	11.0	11.1	12.1	2.5	12.3	10.6	1.6
0.5	9.0	9.3	10.1	2.8	10.3	8.6	1.2

Following the deforestation experiment of Lal & Cummings (1979) at IITA, Nigeria, Lal (1981) determined water retention capacity and infiltration rate after several maize cropping with different tillage and fertilization treatments. Averaging the results across post-clearing treatments gives an indication of the duration of the effect of clearing method, although absolute values are influenced by the post-clearing land use. It was found that after 3 cropping cycles the previous clearing method had no significant effect on water retention capacity anymore, although there was a tendency of declining water retention at low suction in the sequence slash, slash/burn, mechanical clearing (Table 10). More pronounced were the differences in water infiltration rate, also showing a decline in this sequence. Soil tillage had a clear negative effect on water retention capacity at low suction, data being averaged across clearing and fertilization treatments. Unfortunately, data on water infiltration rate with different cultivation methods were lacking.

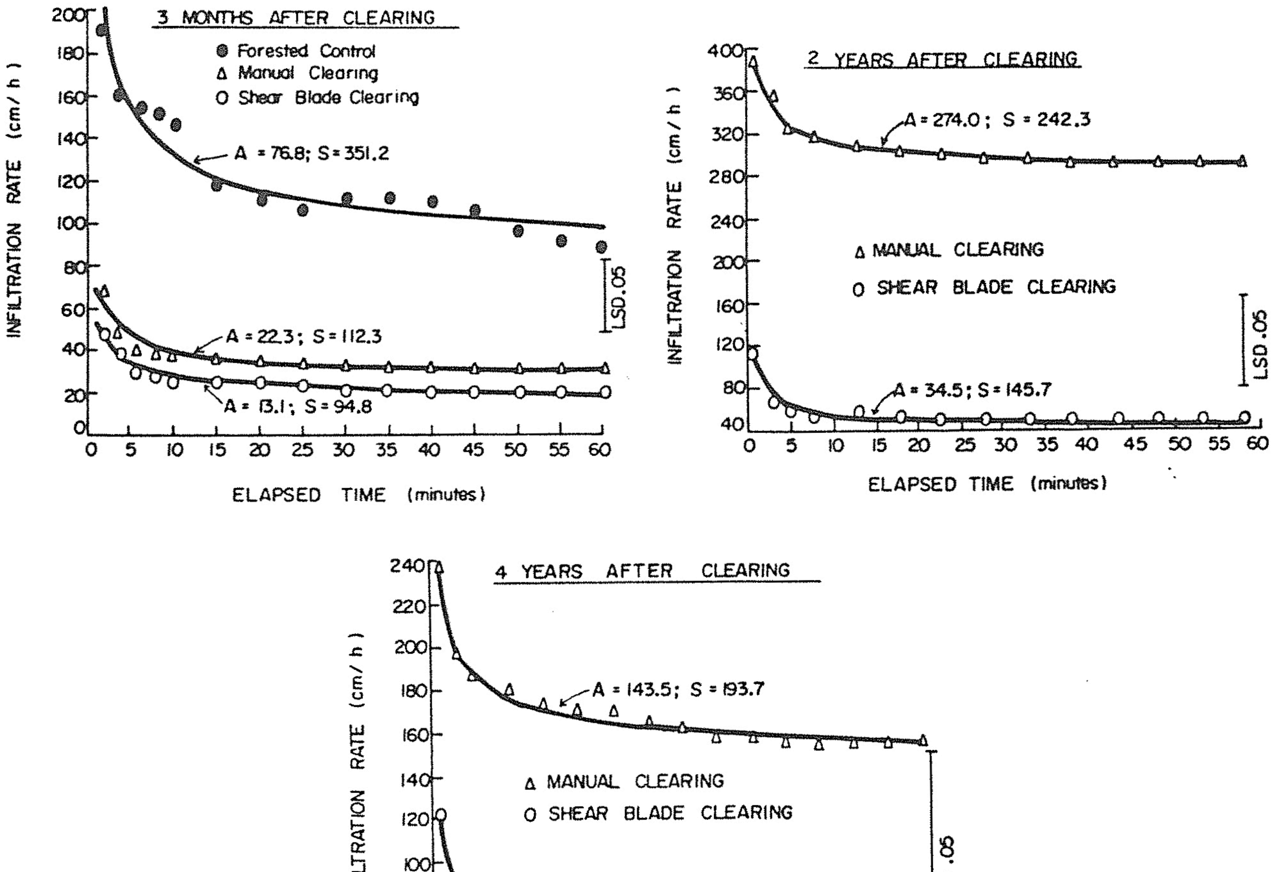

Figure 5: Water infiltration rate shortly after deforestation and after different cropping times following deforestation. Solid curves were fitted by Philip's infiltration rate equation. A=transmissivity in cm.hr^{-1}; S=sorptivity in cm.hr^{-1} (Ghuman et al., 1991)

6. The effect of deforestation and subsequent land use on soil fauna

6.1 Changes in soil faunal populations

Land clearing almost invariably leads to a decrease in species diversity of soil fauna and a change in dominant species. It has been reported by several authors that the total soil meso-/macrofaunal density also declines, but this measure seems not very useful since it does not reveal changes in the abundance of animals in different functional groups. Lavelle & Pashanasi (1989) found that the number of macrofaunal taxonomic units in the top 30 cm of the soil had decreased from 41 under a Peruvian rainforest down to 18-32 under various land uses. Collins (1983) found back only 6 out of the original 25 forest termite species after clearing a forest in Sarawak. In Surinam, Janssen & Wienk (1990) found the number of taxa of the litter-dwelling fauna (meso- plus macrofauna) to decrease from 98 under a forest to 47-55 under various crops or grasses. In the mineral toplayer of plots varying in land use the number of meso-/macrofauna taxa decreased from 56 under forest to 21-30 under cultivation; another sampling showed a decline from 34 under forest to 16-28 under pasture or fallow.

In Kenya, Kooyman & Onck (1987a+b) found more termite species under pasture than under crops (pasture: 16, maize: 7), as was earlier also reported by Wood et al. (1977). Fields under permanent crops (banana, coffee, tea) harboured more species than fields under annual crops. These differences are probably related to differences in intensity of soil disturbance by tillage and in organic matter content of the soil. Termite abundance was highest under crops which leave many crop residues. Application of mulch on the soil surface increased the number of termite tunnels in the soil.

Earthworm activity usually declines with cultivation of the land. Moreau (1986) found that within 1 year of cultivation after forest clearing the abundance of earthworm casts as observed under forest had disappeared. After fallowing of the plot to forest, earthworm activity increased again. A change in dominant earthworm species may also occur, as shown by Critchley et al. (1979) in a bush clearing experiment in Nigeria. In the bush plot casts were produced by both *Hyperiodrilus* and (to a lesser extent) *Eudrilus* species, but in the cleared and cultivated plot mainly the latter species was active. The same phenomenon was reported by Aina (1984), comparing earthworm activity under secondary forest and under long-term continuous cassava in Nigeria. Also Kang & Juo (1986) found a drastic decrease in *Hyperiodrilus* activity after 10 years of continuous cropping, which they attributed to the decline in fresh and humified organic matter content and to the change in microclimate.

A totally different picture is found when looking at the effects of conversion of forest to pasture. A common feature is a strong increase in earthworm population density. Lavelle & Pashanasi (1989) reported a 4 to 6 times higher number of earthworms under pasture than under forest. They also observed a shift in the species dominance: in forest soil mainly litter feeding epigeic and anecic species were present, whereas in the pasture soil the earthworm population was almost exclusively made up of the endogeic species *Pontoscolex corethrurus*. The importance of this earthworm is clearly shown from the fact that it formed no less than 91-96% of total macrofaunal biomass in pasture soil. In Costa Rica, Schouten & Senhorst (1990) found *P. corethrurus* to make up 86-100% of total earthworm population under both forest and pasture. In this study no clear pattern existed in population density between land uses, as on the one location higher numbers existed under forest soil than under pasture, but on the other the opposite was found. The authors tried to relate this difference with differences in physico-chemical soil characteristics (texture, pH, organic matter content, compaction) and time after burning, but could not indicate any clearly causal relationship.

6.2 Factors involved in the decline in soil faunal populations

The effects of deforestation on soil fauna can be divided in direct and indirect effects. The direct effects result from the damage done to soil faunal habitats by soil disturbance during the clearing process itself. This damage concerns e.g. soil compaction, scraping off of topsoil, mixing of soil layers and heating up of the soil during burning. The indirect effects result from the change in micro-environmental conditions after removal of the forest cover. These effects concern e.g. the change in micro- and meso-climate (temperature, air/water stress) in the soil and the decline in organic matter input and change in its chemical composition. The subsequent use of the cleared land for cultivation may lead to further disturbance of the soil and thus may enhance the degeneration of the soil habitats.

As soil fauna may strongly affect the physical structure of the soil, the effects of deforestation and subsequent land use can not be considered within a simple one-directional context, in which the fauna is passively subjected to various stresses. Concerning the direct effects it is clear that the fauna can only play the role of victim, whose habitat is disturbed. For the indirect effects, however, they may - at least in the long run - reduce part of the stresses by modifying the soil environment. Since deforestation provokes a sudden and very drastic change in the soil faunal environment and since many soil formation processes are very slow, the direct effects will dominate initially. Only after a prolonged time (years?) a new faunal community may establish, which is adapted to the new soil conditions.

Lavelle & Pashanasi (1989) performed a principal component analysis on their data on soil faunal populations under various land use practices. They found two major differentiating factors between land uses. The first and most important factor was the type of vegetation, which differentiated forests from pastures, whereas cultivated land and fallows took an intermediate position. On the forest side of the differentiating vector, the macrofauna population was characterized by a high population density but a low biomass, due to the importance of termites and various litter-dwelling epigeics. On the pasture side of the vector the macrofauna population was strongly dominated by the earthworm *Pontoscolex corethrurus*, resulting in a low population density but a high biomass. The second factor represented the physical protection of soil by vegetation, which shows that in conditions of a high degree of exposure to weather influences the surface dwelling fauna (termites, ants) tends to disappear and fauna accumulates in deeper layers. This factor separated crops with a poor soil cover from forest and improved pasture, the latter two having a dense cover. It may be hypothesized that factor 1 (effect of vegetation) combines effects of (degree of) soil disturbance due to land cultivation, and amount and type of organic matter input, since these are the major differences among land use types (apart from degree of exposure, which is factor 2). In the subsequent sections these effects will be analyzed in more detail.

Use of fire

One of the potentially very damaging steps in the clearing process is the burning of the forest debris, since this can lead to a drastic heating up of the soil, killing soil fauna and destroying soil organic matter (Figure 6). The effect of burning depends on its intensity and frequency. If burning occurs with the trees piled in windrows, then a very hot burn is obtained on small areas. Soil temperatures exceeding 200 degrees Celsius have been measured for the topsoil layer, whereas in the upper 20 cm temperatures were above 70 degrees Celsius (Ghuman & Lal, 1989), thus high enough to kill all soil fauna. Raison (1979) reported a partial sterilization of the soil down to a depth of 20 cm after tree burning. Although the killing of soil fauna may be almost complete in these situations, the effect is limited to the small land strips under the windrows. A rapid recolonisation of the sterilized strips from neighbouring zones is possible. Without piling, heating will be less intense, so part of the fauna may survive, but a larger area of the cleared plot is affected. With repeated burning reestablishment of fauna after the first burn may be hampered.

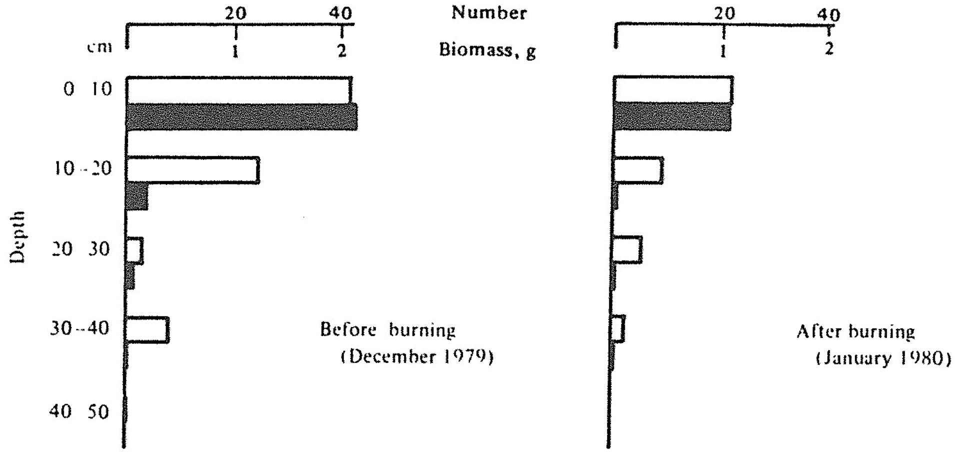

Figure 6: Vertical distributions of density and biomass of soil macro animals (per 50 cm square) before and after burning (Watanabe et al., 1983)

Change in microclimatic soil conditions

The increase in maximum soil temperature and the lower moisture content of the toplayer after deforestation force animals which cannot withstand dry conditions (i.e. those with a weak cuticle) to disappear or to move to deeper soil layers. Drought-resistant animals will then become dominant in the toplayer. There seems to be an inverse relationship between the size of soil invertebrates and their individual resistance to temporarily unfavourable conditions of soil temperature and moisture. Under forest, therefore, macrofauna tends to dominate, whereas under the more extreme conditions of a cleared plot micro- and mesofauna mostly prevail. This was illustrated by Janssen & Wienk (1990), comparing the litter fauna of a recently cleared plot under various crops. They found that under cassava, being an open crop offering little protection to environmental extremes, drought resistant taxa such as centipedes and certain beetle families dominated, whereas these were hardly found in *Pueraria* litter, having a higher moisture content and a less extreme maximum temperature. On the other hand, more sensitive animals such as earthworms were encountered under *Pueraria*, but seldom under cassava. Hauser (1992) showed that exclusion of rain from a site cleared from 4-year old bush in Nigeria resulted in an immediate suspension of earthworm activity, which even was not resumed when the rain was allowed to enter dry plots again. Figure 7 shows that also shading had a particularly strong influence on earthworm activity; the effect of presence or absence of weed regrowth in this experiment was mainly attributed to additional shading and not to its litter supply, since the dominating earthworm species (*Hyperiodrilus africanus*) does not feed on litter (Madge, 1965). Hutson & Luff (1978), discussing the importance of micro-climate in determining the species of Collembola on reclaimed industrial sites, stated that most members of this taxon require a relative humidity of at least 90% to survive for any extended period. Many of the taxa they sampled in bauxite mine plots were poorly adapted to desiccation, so the harsh microclimate of the open planted areas may be harmful to them.

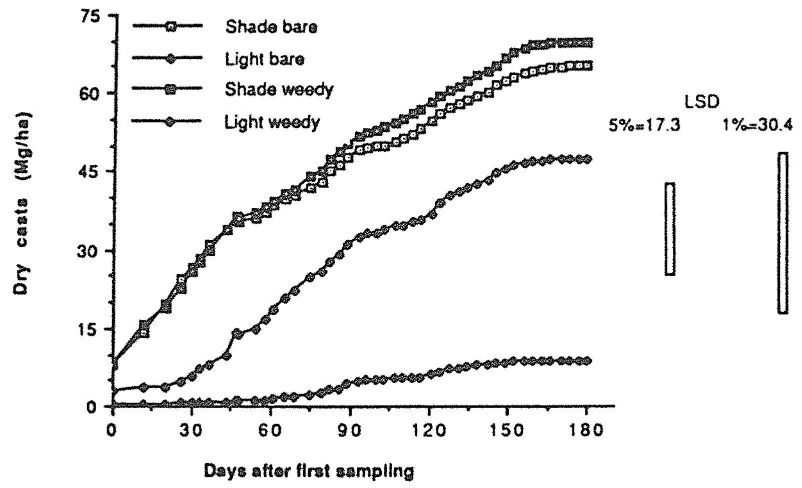

Figure 7: Cumulative casting (Mg.ha^{-1} dry matter) in a plot cleared from 4 year old bush on an Alfisol, S.W. Nigeria, as affected by shading and weeding (Hauser, 1992)

Change in physico-chemical soil characteristics

As shown in the previous paragraphs, a certain degree of soil compaction is almost inevitable during or after forest clearing, although large differences do exist depending on the clearing method used. The effect of soil compaction on soil fauna arises from an alteration of (i) the air/water balance of the soil due to changes in porosity; (ii) the temperature regime of the soil; (iii) penetration resistance of the soil for burrowing animals, which depends on the combined effects of bulk density and matric potential of the soil, reflected in the soil strength.

Brussaard & Van Faassen (1991) reviewed some of the literature on the effect of soil compaction on various soil inhabiting animals. They cited research of Dexter (1978) and McKenzie & Dexter (1988a+b) on the axial and radial pressures exerted by earthworm species in soils. It was found that the better ability to overcome high values of soil strength occurred with a species of the endogeic type, for which it is of clear importance to be able to penetrate compacted soil. An anecic species was not able to survive under such conditions. For the endogeic species *Pontoscolex corethrurus* in Costa Rica, Schouten & Senhorst (1990) found that it was not able to penetrate compacted soil from the surface, but entered a compacted strip from the side, where the soil was not compacted. Once in the soil, *P. corethrurus* even showed a preference for the compacted plots. This might be related to a more favourable soil water condition and to the fact that compacted soil offered the worm a higher organic matter content per unit volume of ingested soil.

Further disturbance of the soil faunal habitats may occur during cultivation of the land. In soils with frequent human disturbance animals which build (semi-)permanent nests at or just below the soil surface are not likely to find suitable conditions. Studying termite populations in Kenya, Kooyman & Onck (1987a+b) observed that species diversity and population densities decreased with increasing intensity of cultivation. Especially those species which live in the upper few centimetres of the soil, and thus are most susceptible to tillage operations, disappeared after cultivation of the land. Most species with diffuse and deep nest systems seemed to easily survive disturbance by cultivation, although in some cases repeated destruction of the ventilation shafts of the nest was probably a disturbing factor. Lal (1976) and Lal & Akinremi (1983) showed ploughing may also lead to a strong decline in earthworm activity (Table 11), which is probably related to an increase in soil temperature and a decrease in soil water content and organic matter content.

Table 11: Effect of ploughing on the casting rate of *Hyperiodrilus africanus* for different cropping sequences (Lal, 1976)

Cropping sequence	Number of casts (m^{-2})		Equivalent weight ($t.ha^{-1}$)	
	No-till	Ploughed	No-till	Ploughed
Maize - Maize	1060	90	41.3	3.5
Maize - Cowpea	1220	372	47.6	14.5
Pigeonpea - Maize	464	100	18.1	3.9
Soybean - Soybean	42	3	1.6	0.1
Cowpea - Cowpea	28	36	1.1	1.4
Mean	563	120	22.0	4.7

Tillage also leads to a mixing of the litter layer through the soil, resulting in a more gradual transition of the organic topsoil to the mineral subsoil. For soil fauna this may mean a reduction in total niche space for those animals which specifically feed on litter and do not or only scarcely burrow into the soil (e.g. epigeic earthworms), but at the same time an increase in niche space for animals which live and feed in the organo-mineral layer (e.g. anecic or endogeic worms). The total organic matter content of cultivated soil is invariably lower than that of the previous forest soil, but the higher nutritious value of this organic matter may enable the soil faunal population to stabilize or even increase its density. Van der Werff (1983) found that the topsoil under primary forest in Surinam with an organic matter content of 4.5% supported a mesofaunal biomass of 700 $mg.m^{-2}$ (dry weight). Under maize, a higher mesofaunal biomass was found (1100 $mg.m^{-2}$), while total organic matter content was lower (2.4%).

6.3 Consequences of changes in soil faunal populations for the soil physical conditions and crop yields

The studies referred to in the previous paragraphs describe changes in soil faunal populations and in soil physical properties after disturbance of the ecosystem. However, since both changes were a reaction on the same disturbing agents (i.e. clearing and/or cultivation), these studies do not allow to causally relate the two parameters. It is, therefore, difficult to indicate what has been the contribution of the changes in soil fauna to the changes in soil physical condition. Theoretically, the direct effects of clearing and cultivation on soil physical condition may have been so strong that the (indirect) effects, originating from reduced faunal activity, were overruled. The possible role of soil fauna in soil amelioration, therefore, will be analyzed on the basis of experiments in which soil fauna has been manipulated without disturbing soil physical conditions. These are e.g. experiments in which fauna has been eliminated chemically or stimulated by adding specific types of organic matter, or experiments on rehabilitation of degraded land by introduction of fauna.

The potentially drastic nature of the change in soil physical conditions after disturbance of soil fauna are clearly illustrated by an experiment of Clements (1978), who eliminated earthworms (and probably part of the other fauna also) from a pasture by regular insecticide application. It was found that earthworm elimination resulted in an accumulation of litter at the soil surface, and, consequently, in a lower soil organic matter content (Table 12). It also led to an increased bulk density. The most drastic effect, however, was on hydraulic conductivity, which after earthworm elimination was only 4-7% of that of the control plot with earthworms. Aina (1984) found that destruction of existing earthworm channels in a forest soil by tilling the soil to a depth of 15 cm reduced water infiltration rate by 67% due to loss of macroporosity. If next, earthworms were eliminated from the soil, then water infiltration rate further declined during the following months. Without elimination of earthworms (mainly *Hyperiodrilus* spp.), infiltration rate increased again. In cultivated soil, earthworm elimination had a similar, but less pronounced effect. The effect of earthworms on water infiltration rate depends on the burrowing nature of the species, since it is important that the pores they create are connected to the surface (Bouma et al., 1982). The strongest effect on water infiltration, therefore, have the anecic species, whereas epigeic or endogeic species have comparably little effect (Syers and Springett, 1984; Springett, 1985).

Table 12: Effect of pesticide application for 7 years on earthworm population and soil properties (Clements, 1978)

	Low N		High N	
	Control	Pesticide	Control	Pesticide
Earthworm number (m^{-2})	37.0	0	30.1	0
Surface litter accumulation ($t.ha^{-1}$)	0.34	5.21	3.23	15.50
Soil organic matter content (%)				
0-50 mm depth	5.18	4.68	5.30	4.63
50-150 mm depth	4.40	4.23	4.52	4.19
Bulk density, 0-100 mm depth ($g.cm^{-3}$)	1.17	1.37	1.20	1.27
Hydraulic conductivity ($m.day^{-1}$)	17.79	0.67	20.07	1.39

Reports on the effect of termite exclusion on water infiltration rate are variable. Kooyman & Onck (1987a) found that suppression of termite activity hardly affected the volume of large pores in the soil, but increased the small pore volume, which they explained from the collapse of existing termite tunnels, now that they were no longer maintained. Remarkably, this led to an increase in hydraulic conductivity, which seemed to arise from the fact that water infiltrated through the porous soil matrix and did not follow the relatively wide termite tunnels. This might be due to the very high capillary storage capacity of this soil, making that the tunnels remain air-filled after rainfall. Also Spears et al. (1975) found increased water infiltration rate after termite elimination, which they attributed to a higher capillary porosity (pores were blocked by fine clay particles in termite-infested soil), larger soil aggregates and a higher surface soil organic matter content. Furthermore, the authors showed that the surface of termite tunnels was significantly more water repellent than the surface of adjacent peds and concluded that, therefore, these structures may in fact decrease infiltration. In contrast with these results, Elkins et al. (1986) found that elimination of termites resulted in increased runoff from bare desert soil, which after 4 years showed a 30% reduction in total porosity and a 42% reduction in water infiltration rate. The difference between these studies may be related to difference in duration of the experiments. In the long-term trial of Elkins et al. (1986) it is likely that the strong decline in total soil porosity due to collapse of old termite tunnels overruled other effects.

Very few studies have dealt with effects of ants on soil physical properties. Wilkinson (1975) showed that ants can also strongly affect water infiltration rate of a soil. He observed a 6-fold increase in equilibrium infiltration rate of a savanna soil due to ant activity.

Apart from human interference by tillage, which may have both positive and negative effects on the soil condition, burrowing by soil fauna provides the principal way to alleviate soil compaction and poor porosity. A key parameter in soil macrofauna activity is the availability of organic matter, since this provides the animals' primary source of nutrients and energy. Manipulation of organic inputs, therefore, offer opportunities for testing the effect of faunal activity on soil condition. In Nigeria, Tian et al. (1992a+b, *submitted*) compared the effect of various types of prunings on soil faunal activity and crop yield. They found that microclimatic conditions of soil with a mulch layer were more favourable for soil fauna than in unmulched plots, due to the decrease in soil temperatures and increase in soil water content. Prunings of low nutritious quality, which decomposed slowly and, consequently, had a more durable effect on microclimate, were found to promote the abundance of termites. Highly nutritious prunings attracted earthworms and ants. Also in Nigeria, Kooistra et al. (1990) demonstrated that the application of crop residues as mulch resulted in much looser topsoil, higher porosity and a better infiltration rate than in unmulched plots. Consequently the mulched plots were less prone to erosion. The authors attributed these differences to differences in soil faunal activity. It was shown by Kooyman & Onck (1987a) that soil structure improvement after mulching may indeed be related to an increased faunal activity. Application of mulch on compacted soil in Kenya resulted in an increased number of termite tunnels compared to the unmulched plot. Also the number of fine (0.5-0.9 mm) and medium-sized (1.0-1.5 mm) biopores had increased over the full sampled depth of 50 cm. They mentioned that part of the non-termite biopores may originally have been constructed by termites and may subsequently have been occupied by other fauna or plant roots. The favourable effect of termite tunnels for root growth was already demonstrated by Robinson (1958), who found growth of coffee roots in termite worked soil was better than in soil without termite tunnels. In the experiment of Tian et al. (*submitted*) crop yields had increased by 40 to 70% in plots mulched with *Leucaena* prunings compared to unmulched control. Mulching at a rate of 5 ton *Leucaena* prunings per ha in combination with an N-dose of 45 kg.ha^{-1} resulted in higher crop yields than application of 135 kg.ha^{-1} nitrogen without adding prunings. This difference may result from an improved soil physical condition due to increased soil faunal activity, but also from nutrient release from decomposed prunings.

The potentially large benefits of earthworm manipulation for soil rehabilitation after deforestation was clearly shown by experiments of Pashanasi et al. (*in preparation*) at Yurimaguas, Peru. By adding sawdust to bags of soil inoculated with the earthworm *Pontoscolex corethrurus*, they obtained a 10-fold increase in worm biomass after 2 months. Small tree seedlings planted in this earthworm-worked soil showed a 300% better growth than those which were planted in the original soil without earthworms. Field experiments with introduced *P. corethrurus* showed average increases in grain production of 23-60% for the first crop (maize) and of 50-96% for the second crop (upland rice), depending on the quality and quantity of organic matter inputs. The effect of earthworm introduction into pastures was demonstrated by Stockdill (1982) in New Zealand, who reported an almost 30% increase in grass yield after establishment of the earthworms.

It can be concluded that the reduction in soil faunal activity leads to a more compact soil with a lower porosity and a poor water infiltration rate. This structure is highly unfavourable for plant growth. The strong decline in water infiltration rate is of the highest importance for soils of the humid tropics, since this inevitably leads to an increased superficial water flow, thus enhancing the risk of sheet erosion. The low production levels which farmers face soon after bringing the land under cultivation, are not only related to a chemical exhaustion of the soils, but definitely also to the decline in physical soil properties. Manipulation of soil fauna seems to offers great opportunities for improving this situation.

7. Conclusion

Deforestation has immediate, strongly negative effects on the physical condition of the soil and on the soil dwelling fauna. The disturbance of the soil starts with the clearing process. Manual clearing only slightly disturbs the soil, resulting from foot traffic, from the falling or dragging of trees, and from subsequent burning. In contrast, mechanical clearing by heavy equipment can totally ruin the physical structure of the soil down to several decimeters depth. The damage done to the soil structure by mechanical clearing almost invariably includes soil compaction in top- and subsoil, accompanied by a reduction in total soil porosity and by a shift to smaller pore sizes. Consequently, water retention characteristics of the soil change and hydraulic conductivity and, in particular, water infiltration rate are significantly reduced. The soil thus becomes more susceptible to puddling and erosion. The changes in abiotic and biotic environment following deforestation, have important consequences for the soil faunal population. The more intense exposure of the soil to effects of wind, rain and sun after total removal of the forest cover results in a less favourable microclimate for most soil fauna due to the higher temperature and soil moisture fluctuations. It also leads to an accelerated decomposition of soil organic matter and thus to a decline in food resources for soil fauna, which effect is further accentuated by the strongly reduced input of fresh organic matter after deforestation. The data show that deforestation invariably leads to a lower species diversity and a change in dominant animal species. In most cases total faunal activity is also strongly reduced compared to the forest soil.

The land use after deforestation determines whether the soil has an opportunity to recover or whether further disturbance of the soil occurs. It is a clear fact that the huge damage done during mechanical clearing will be very hard to repair during cultivation. From the scarce literature it can be deduced that land uses which leave the soil uncovered for a large part of the year (especially during the rainy season) are deleterious. A high return of organic matter to the soil has a favourable effect, through its protection against weather influences and its stimulation of soil fauna. Tillage may alleviate soil compaction and improve water infiltration, but also leads to further disturbance of soil fauna, so reducing the natural regenerative capacity of the soil.

Under forest the burrowing activity of soil animals provides for a stable and highly porous soil structure, ensuring an easy root penetration into the soil, a proper balance in water and oxygen supply to the roots and a rapid infiltration of rain water. The soil disturbance during clearing and cultivation, together with the reduction in soil faunal activity make the originally biogenic structure of the forest soil change to a structure of a more physicogenic nature. This is seen from a shift from a loose, aggregate soil with large quantities of passage and excrement pedofeatures such as compound packing voids and earthworm casts, to a more compacted soil with dense, angular aggregates, planar voids and water stagnation pedofeatures. This soil structure is highly unfavourable to plant growth, whereas the poor water infiltration capacity of the soil may lead to increased losses of fertile soil through erosion.

For many tropical countries harvesting timber from rainforests is a very tempting and seemingly inexhaustible source of income. Huge areas have been and are being deforested, often without proper concern about the further use of the land after clearing. The demand for land for agricultural purposes also leads to clearing of forested land, which may be abandoned again after some time. Consequently, vast and growing areas of virgin forest have been turned into degraded, unproductive land. The worldwide rapid decline in forest area calls for measures to preserve the remaining virgin forests. An essential element in this should be the development of land use systems allowing timber and food production at an economically acceptable level on the currently cultivated land, without the need to clear new land. The establishment of such production systems, however, is hampered by the rapid decline in physical and chemical condition of the soil soon after clearing. Whereas a decline in chemical soil fertility may be counteracted by application of fertilizers or lime, a decline in physical soil condition is not easily compensated for, since *soil structure forming and stabilizing elements are in decline, while structure degrading forces are boosting*. Any action, negatively affecting the soil structure, therefore, should be avoided as much as possible.

Various authors described the crucial role of soil fauna for developing sustainable land use systems based on integrated soil fertility management, in which a limited use of external inputs is combined with a careful manipulation of soil organic matter and soil fauna (Woomer & Swift, 1992; Brussaard et al., 1991, 1992). Land clearing leads to a strong decline in soil faunal activity and sets in motion a process of degradation of the soil physical condition, both of which are in striking conflict with the wish to develop a sustainable land use system. The challenge for a proper soil management after deforestation is to not only slow down this process of soil deterioration, but to transform it into one of soil regeneration, creating soil conditions favourable to sustained plant production. Management of soil fauna has to play a central role in this, since the soil animals - small but extremely numerous - provide the major prospect to get a soil condition as close as possible to that of forest soil, in which possibilities for water uptake and gas exchange are balanced and nutrient losses are minimal.

In view of the drastic changes in soil microenvironment during deforestation, it is not likely that those faunal species which dominated in the forest soil will also thrive in the new soil environment. The sudden nature of the change makes it almost impossible for animals to adapt to the new conditions. From experiences with rehabilitation of former mine areas (Majer, 1981, 1989) or newly reclaimed polders (Van Rhee, 1969; Meijer, 1989), it is known that natural recolonization of the soil by macrofauna is an extremely slow process and that easily barriers are formed which totally block invasion. It will be necessary, therefore, to either make allowance for faunal survival during the clearing process, or to assist in the building up of a new faunal population by introduction of suitable species and by creating a more favourable micro-environment for soil fauna. Incomplete clearing of a forest, in which small dispersed plots are preserved to form a starting point for adaptation of fauna and spreading to the cleared land, would be an option from the point of view of fauna survival. In large-scale forest clearing operations this approach seems an illusion, but with selective harvesting of trees as practised with silviculture in secondary forest, it does offer possibilities for soil fauna management. In agriculture the use of cover crops or forest-derived cropping systems such as agroforestry seem promising, since they contribute to a more favourable micro-environment for soil fauna by providing shade and organic matter, so creating a wider range of niches in which they can survive the clearing or from which they may recolonize the cleared land.

For the development of such systems, it is essential to have a thorough understanding of the processes and changes occurring in the soil before, during and after deforestation and, especially, of the role of soil fauna in these. Until now, mainly scattered information on separate aspects of the degradation process is available, and only few studies deal with the complete land use succession, starting from the virgin forest and continuing until several years of cultivation. However, also these studies mainly focused on physical or chemical aspects of soil degradation and left the role of soil fauna largely concealed. There is urgent need for integrated studies relating physical soil degradation to changes in soil fauna, considering both the changes resulting from the clearing process itself, as those resulting from the subsequent land use.

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