Introduction

While investigating the geology of Central America, Sapper (1903) depicts the first soil map of the region, including the territory of Costa Rica. However, soil science in the country begins a little later when Prescott (1918) and Bennett (1926) selected lands to plant lowland crops in the Caribbean Region. During the 1940s, the University of Costa Rica (UCR) reopens and the Inter American Institute of Agricultural Sciences (IICA, Turrialba) starts operations in Costa Rica. This was a remarkable landmark for the country’s agricultural research, since many areas of knowledge were housed in Faculties or Departments at UCR, and medium-term agricultural (soil) research projects were carried out at IICA. During these years the first works on soil analysis for soil fertility purposes were conducted in a small laboratory at UCR in collaboration with the Departamento Nacional de Agricultura de la Secretaría de Agricultura and Ganadería (Ramírez 2001).

At the beginning of the 1950s, with the expansion of medium- and high-altitude crops (mainly coffee, sugarcane, and vegetables), soil studies were carried out in the Central Valley (Dondoli and Torres 1954, COSTA RICA-MAI 1958). Government-sponsored colonization programs for the northern region in the 1950s and 1960s led to increased soil knowledge for this region (COSTA RICA-ITCO 1964, Sandner et al. 1966). In December 1955 the Agricultural Research Center of UCR was established as an institution that produced important research papers on Costa Rican soils until date.

It is during the 1960s that a group of soil scientists at IICA, Turrialba (now CATIE), promoted soil science knowledge in Latin America; as a result of this effort, other areas of soil science developed, and books in Spanish were prepared on soil microbiology (Blasco 1970), soil chemistry (Fassbender 1975), soil physics (Gavande 1973, Forsythe 1975), and later on soil genesis and classification (Alvarado 1985), soil clay mineralogy (Besoain 1985), and soil and forest ecosystems (de las Salas 1987). Most of the knowledge generated until 1960 allowed the drafting of the first maps of potential land use in Costa Rica at a scale of 1:750,000 (Plath and van der Sluis 1965, Coto and Torres 1970), as well as the first semi-detailed taxonomic soil map of the country (USAID 1965) and the characterization of Costa Rican soils on the Soil Map of the World (FAO-UNESCO 1976). In 1960, the Programa Cooperativo Oficina de Café-MAG initiated activities related to nutrition and fertilization of coffee plantations. At the end of the decade Fertilizantes de Centroamérica (Costa Rica) S.A. (FER- TICA) began operations, a company that for more than 30 years dominated the market of this type of products and promoted its use exponentially.

By the mid-1960s, the Tropical Science Center (TSC; a.k.a. Centro Científico Tropical, CCT, in Spanish) and the Organization for Tropical Studies (OTS, or OET in Spanish) initiated their activities in Costa Rica. Until the mid-1980s TSC focused its attention mostly on life zone ecology and land use capability / suitability studies throughout the country. Examples of their land use assessments are the evaluations conducted in the Salitre indigenous reserve (Tosi 1976, 1979).
Description of Major Soil Orders

This section describes the usefulness and importance of Costa Rican soils for agriculture, following soil taxonomy standards. The analysis includes a summary of the type of areas occupied by each major soil type; the crops planted there; its geographic distribution within the country and position in the landscape; its probable means of origin; the principal mineralogical, physical, and nutritional characteristics of each group; and the management practices that could be applied to each to achieve best its productive potential. In this way, this section can be considered an update to the findings presented by Bertsch et al. (2000).

It is possible to find in Costa Rica all 12 major soil orders recognized by soil taxonomists except desert soils (Aridisols) and frost soils (Gelisols). Six of these 10 have major agricultural relevance: Inceptisols (38.6%), Ultisols (21%), Andisols (14.4%), Entisols (12.4%), Alfisols (9.6%), and Vertisols (1.6%); the percentages mentioned represent the relative area each soil order covers (Mata 1991).

Entisols

Entisols are very recent soils that exhibit little development. Therefore it is not possible to distinguish any defined horizon sequence in the profile. The most common Entisol suborders in the country are fluvents, aquents, orthents, and psamments (i.e., soils derived from recent alluvial deposits, under stagnant water, shallow soils on hard rock, and sandy textured materials, respectively). The presence of psamments in coastal beach fronts or elevated coastal structures is a consequence of continental uplift due to plate tectonics activity (Fig. 4.1).

Recent alluvial deposits lead to the formation of fluvents in areas where frequent flooding does not allow soils to remain undisturbed long enough to permit the development of horizons. Under these conditions, a sequence of layers of contrasting particle sizes occurs. In the same geomorphic surfaces, these soils turn into aquents when the water table remains near or above the soil surface and restricts soil development for long periods of time. Orthents, being the most abundant Entisols, prevail on rocky hillsides with low temperatures and/or very erosive rains, recent volcanic depositions such as ashes or lava, and the presence of parental material resistant to weathering. Other Orthents are found in low relief portions in regions of rhyolithic origin with less than 1300 mm of precipitation in the dry Pacific areas.

Most Entisols are of limited agricultural potential due to their high flood risk, restricted soil rooting depth, low fertility status, or location on steep slopes. Their use by humans should be restricted to forestry or conservation activities. Nevertheless, in Costa Rica these soils are frequently used for annual crops, and extensive cattle operations on both
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flat and steep lands. Owing to their minimal development, these soils reflect the properties of the parent material out of which they were formed, which is why they display a very varied mineralogy. In general, they are not very suitable for agricultural purposes because of shallow rooting depth, reduced conditions, and, as noted, frequent flooding and high susceptibility to hydric and aeolian erosion.

In wetlands, aquents and fluvents are associated with aquepts (Inceptisols) at the Caribbean side covered by natural vegetation dominated by yolillo palms (*Raphia* spp.) and cativo trees (*Prioria copaifera*) and mangrove vegetation in the Pacific coast, recently exploited for banana and oil palm production, later for charcoal production and today in danger by a possible large sediment deposition if the proposed hydroelectrical plant at Diquís becomes a reality (Torrealba et al. 2011).

**Fig. 4.1** Distribution and characteristics of Entisols of Costa Rica.

Once drained, these soils are used to plant bananas, cocoa, and oil palm. Orthents form on thin volcanic ash deposits over lava flows (e.g., in Cervantes, Cartago province, and Paso Canoas, Puntarenas province). Although they are not very productive, they may be heavily fertilized and planted with vegetables serving nearby markets. In other regions, where the exposed rock is not really hard (e.g., as in the case of rhyolitic materials in Guanacaste) they are used for ranching purposes and, recently (and with very little success), for forestry. At the hillsides in the Southern and Central Pacific regions orthents are commonly used for low technology bean planting (“frijol tapado”).

**Inceptisols**

Inceptisols are widely distributed in Costa Rica. Because the country is geologically and geomorphologically relatively young, Inceptisols cover about 39 percent of the coun-
Soils of Costa Rica

The young age of the soils also implies that they strongly reflect their parent material, including Lithic (rock), Fluventic (riverine), Andic (volcanic), Vertic (clay mineralogy), or Oxic (trivalent cation accumulation) properties. They are common on hillsides where erosion due to a combination of earthquakes and heavy rainstorms induces landslides, which limit soil formation to a profile with very weak horizon development. Under these conditions, a typical Udepts toposequence includes Vitrandic Dystrudepts (high volcanic glass, coarse textured soils) in the upper positions, Humic Dystrudepts (high organic matter content soil) in the middle positions, and Typic Dystrudepts (soils with low bases status) in the lower positions of the landscape.

The Ustepts are found in rolling and flat geomorphic surfaces. Among these, Dystrustepts (low base saturation) and Haplustepts (little soil development) form from the weathering of relatively old alluvial and/or colluvial fans. In the same environment, Inceptisols classified as Aquepts are found when there is a perched water table. These are the most important soils for agriculture of the lowlands less than 100 meters above sea level. A sulfidic horizon forms where brackish water and mangrove vegetation occurs along coastal back swamps. These are classified as Sulfaquepts. The most important Inceptisols are found in alluvial valleys in the coastal plains. These soils have the highest agricultural potential of the country and can be found in the valleys of the Tempisque, Bebedero, Tárcoles, Parrita, Térraba, Sierpe, and Coto rivers on the Pacific side, and the Matina, Reventazón, Parismina, Pacuare, Estrella, and Sierpe rivers on the Caribbean side (Fig. 4.2). In many cases these soils develop from basic parent materials such as limestone, from which they inherited their high base saturation, adequate texture, and moisture retention.

Inceptisols (except those with poor drainage) generally

![Fig. 4.2 Distribution and characteristics of Inceptisols of Costa Rica.](image)
have good characteristics for management, since they do not possess the properties of more developed soils, such as cation depletion, that affect management adversely. For this reason, they can be used for a large range of agricultural production activities, including banana, oil palm, sugarcane, cocoa, coffee, staple crops, livestock, forestry and, recently, non-traditional crops such as mango, avocado, cantaloupe, pepper, roots and tubers, tropical flowers, etc. Even the Sulfaquepts along the coast are important for mangrove forestry, shrimp aquaculture, and extraction of salt.

Chemical and mineralogical properties of Inceptisols vary according to their origin. Therefore, their range of chemical characteristics is broad. Each soil tends to include many clay mineral types mixed together, including smectites, allophane, kaolinites, and organic and oxidic coatings (Alvarado et al. 2014a,b). When there is a preponderance of volcanic ash materials some amorphous clay develops. In the alluvial valleys of both the Caribbean and the Pacific sides, montmorillonite is found. The extreme weathering conditions in tropical environments of the El General River Valley result in the formation of 1:1 fractions of clays and oxides in red soils of very high acidity values, and cation depletion. These are the most infertile Inceptisols of the country.

Those Inceptisols used for commercial plantations in the poorly drained lowlands require drainage (Epi- and Endoaquepts). For example, as Eastern banana plantations spread from the slopes toward Limon extensive networks of 1- to 2-meter-deep ditches are required. Such ditches are economically viable only when flood frequency remains low. The fertility of Inceptisols in the North Atlantic Zone is much higher than in the South Atlantic Region because they are developed from volcanic materials spread downslope by rivers. In the South Atlantic Region of the country Inceptisols were formed from much less productive calcareous materials, and are also subject to much greater frequency of flooding.

The fertility of Inceptisols in the Guanacaste lowlands can be greatly enhanced with applications of S and Zn, especially in rice plantations (Bornemisza 1990, Cordero 1994). Moisture availability is critical on these Inceptisols in ustic (long dry season) environments. These properties have been mapped, and used for categories of crop insurance (IICA 1979).

Rice cultivars on Inceptisols in the South Pacific Valleys have been subject to Cu toxicity generated by massive applications of copper-containing Bordeaux fungicides to banana plantations in the 1940s and 1950s (Cordero and Ramírez 1979). Much of this very fertile land had to be abandoned and owing to silt deposition by river flooding they have been rehabilitated for annual crops. During the early days, these lowlands were planted with banana and cocoa without any fertilizer application; at present, improved varieties and higher productivity of oil palm and banana plantations require large amounts of complete fertilizer formulas and drainage systems.

Small farmers, living in government settlements in the Northern and Atlantic regions of the country, plant cereals and roots and tubers using low inputs. Because of the predominantly perudic environments in these regions, the traditional slash and burn system is not practiced since the slashed vegetation does not dry and cannot be burned. This particular problem does not allow for obtaining beneficial effects from liming and fertilizing with added ashes. Normally, the accumulated biomass slowly decomposes with time, releasing nutrients only gradually (Bertsch and Vega 1991).

Andisols

A comprehensive summary of Andisols of Costa Rica is presented by Alvarado et al. (2001). Andisols are formed from volcanic ash deposits and occupy: (a) the Central Valley and surrounding mountains; (b) hillsides of the Guanacaste Mountain Range, (c) the region between Coto Brus and the border with Panama influenced by the Barú Volcano’s ashes, and (d) some regions of the Northern and Atlantic zones where fluvo-volcanic depositions occur (Fig.4.3). Volcanoes are still quite active in Costa Rica, and their activity influences agricultural potential directly as well as indirectly through soil building and acid rain depositions (Alvarado and Cárdenes, chapter 3 of this volume). The emissions of acidic clouds from volcanoes turn into acid rain in nearby zones, which leads to an intensive weathering of the land system, enhancing basic cation leaching and causing considerable loss of crop yields. Although Andisols cover only 14 percent of the nation’s territory, many major agricultural products like coffee, sugarcane, vegetables, non-traditional export crops (flowers, ferns, strawberry), and dairy products like milk and cheese are indeed produced on lands dominated by these soils. Part of the latest large banana boom of the 1990s was settled on volcanic soils of the Northern Zone and parts of the Atlantic Region. In the lowlands, in terms of non-traditional crops, Andisols can produce very good roots and tubers, heart of palm, and a huge range of tropical ornamental plants.

The frequent rejuvenation of these soils by andesitic volcanic ash additions constantly enriched the environment with nutrients. Large depositions of debris, particularly near the craters, allows the formation of Vitrands, while Udands form under repetitive deposition of thin volcanic layers in the middle positions of the landscape in udic environments.
In the lower parts of the landscape, where a distinctive dry season occurs, Ustands are predominant. Andisols of lighter color are found along the Guanacaste Mountain Range, in the north of the country, and originated from the deposition of rhyolitic/dacitic ashes. Andesitic basaltic ashes predominate in the central and southern parts of the country, and give rise to dark-colored soils.

The effective depth of the top soil layer of Andisols generally depends on the magnitude of the volcanic deposition that formed that layer. Deep soils tend to be formed from the deposition of many small layers of ashes, while thin Andisols are formed by one event, which can be of small or large magnitude. It is possible to observe the ash deposition frequency and magnitude in deep road cuts, as well as the presence of paleosols with a different degree of weathering.

Soil particles are generated and distributed initially by the nature of the original volcanic activity, and then sorted by prevailing winds according to particle size and density, creating a textural gradient along the hillsides of volcanic craters. Coarser material is deposited in the vicinity of craters, resulting in sandy to sandy-loam materials. Further away silty loam or loam textures are predominant. Finer textures are found farther away from the volcano, particularly in the B horizons of well-developed soils. This textural gradient notoriously affects nutrient availability and irrigation needs.

Once the original deposition has taken place climate forces predominate. For example, if a moist and cold environment ensues near the volcano, this allows for a weak weathering process of volcanic glass, releasing small amounts of Si, Al, and Fe oxides and hydroxides. If long periods of volcanic inactivity follow, the translocation of the oxides will form a cemented layer (called a placic horizon) wherever an abrupt textural change is present. Farther from...
the crater, allophane becomes predominant. This type of clay is an amorphous and hydrated colloid, which forms organomineral compounds and represents required products of volcanic ash decomposition in humid zones (Alvarado et al. 2014a). Allophane is an unstable clay-size particle of high reactivity that gives a peculiar behavior to these soils. Secondary organomineral compounds possess a very large hydration capacity that enables them to enlarge their total surface, therefore increasing their capacity to retain or exchange cations and anions.

In the Central Valley, farther away from the volcanoes, rainfall decreases and a long dry period permits the formation of a 1:1 crystalline clay named halloysite. This type of clay has shrink and swell properties, low water retention characteristics, and less nutrient retention than allophanes. They are predominant in the brown-yellowish soils of the coffee and sugarcane plantations of the Central Valley. Each mineral type gives a characteristic color to the soils that are formed from them. Dark-colored Andisols are associated with a high allophane content; brown yellowish Andisols are dominated by halloysite; while brown reddish Andisols are related to kaolinite. White-colored Andisols are associated with the presence of gibbsite (Colmet Daage et al. 1973, Besoain 1985).

Owing to the presence of highly stable organomineral compounds, especially in the A horizon, Andisols tend to be very well structured. This results in a high infiltration capacity leading to both good drainage, and good moisture retention characteristics. One unfortunate consequence of these properties is that these soils promote the leaching of nitrate from agricultural systems and human sewage down to underground waters, contaminating ground waters and reducing their value for human use (Reynolds 1991), although these relationships have a variety of applications (Radulovich et al. 1992) that are currently being studied.

These soils have low bulk density and low resistance to tangential forces, making them easy to plow. In Costa Rica this task should be done by animal traction in order to prevent erosion, instead of using heavy machinery that tends to compact the soil (RELACO 1996). Overgrazing causes a similar effect. During periods of high volcanic activity, large amounts of very unstable ashes are deposited as blankets that cover the landscape. This material partially dissolves when subject to alternating dry and moist periods, inducing redistribution of soluble elements at the surface, cementing small pores, and reducing infiltration by crusting. This phenomenon develops into massive erosion, which encourages the formation of colluvio-alluvial fans at the bottom of the landscape. This is the main factor generating catastrophic events when defined as “lahars” or “debris avalanches” (Alvarado, Vega, et al. 2004) in populated areas. Also, these soils are intensively used for agricultural activities that greatly trigger their erosion and cause silting of hydroelectric dams.

Most Andisols have a moderate fertility depending on the composition of their parent material. In general, soils formed from the ashes of the Irazú Volcano are richer in bases than those formed from Poás Volcano materials (Alvarado 1975); Andisols around Barú Volcano in the Southern Region are even poorer than those of the Central Valley. Nutrient leaching in volcanic areas is counterbalanced by new additions of volcanic ash; this process enables nature to maintain the base saturation of the ecosystem. Generally, Andisols have pH values near neutral except in agricultural areas with poor management or where the decomposition of abundant organic matter content of Andisols gradually acidify soils, particularly when large amounts of N are applied. When this happens they do respond to liming with calcitic (Ca carbonate) or dolomitic (Ca and Mg carbonates) products.

The soil fertility potential of Andisols can be estimated by the sum of cations (Ca, Mg, K, Na). Higher values indicate a better condition for crop development and imply that other nutrients are also abundant. In Andisols of the Southern Region, the predominance of plagioclases over orthoclases creates a pronounced K deficiency (Molina et al. 1986, Henriquez and Bertsch 1994). In recent volcanic ashes, N is the most limiting factor for crop production. But P, although abundant in total, creates difficulties for farmers too. P is held tightly by the clay lattices of Andisols so that it is not available to plants. Retention is generally over 70 percent, which is very high, and it can easily reach values of 95 percent. This problem constitutes by far the major limitation for crop development on these soils (Alvarado 1982, Canessa et al. 1987). In addition, B and S can also be tightly held as anions. The application of these two elements is essential for coffee production all over Costa Rica. Andisols formed in the lowlands of fluviovolcanic origin of the Northern Zone and part of the Atlantic Region, along the Sarapiquí, Sucio, Chirripó, Tortuguero, and Destierro rivers, are poorly understood. Under very high temperature and rainfall conditions, they seem to weather to form soils with more nutritional problems than those of the highlands. In addition, the low relief of these areas enables water to accumulate on the surface, thus enhancing soil compaction, particularly in pasture lands.

Owing to the high P retention of Andisols, most crops require large fertilizer applications with soluble P. The exact location and granule size of such fertilizers are important; it should be applied along with light applications of lime that increase the availability of P retained in organic materials. N is also a limiting factor for crop production, except when
Vertisols

Vertisols are found mainly in the Northwest Dry Pacific region of Costa Rica (see chapter 9 on Nicoya and Guanacaste by Jiménez, Carrillo, and Kappelle, this volume), on either plains or depressions where the dry season extends from 4 to 6 months, and are often associated with small patches of similar Mollisols. Although most Vertisols have a neutral or basic status, a few of them located near the bor-
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Vertisols are used intensively for both agricultural practices and—in the Central Valley—for urban development. During the rainy season the main crop on these soils is rice, either flooded or rain-fed. With irrigation and adequate soil water management sugarcane, soybean, melon, cotton, or even hot chili pepper and sauce tomato can be grown. Trees grow poorly on these soils, owing to root damage caused by alternate seasonal periods of dryness and water excess. Thus, commercial forests are neither abundant nor recommended on Vertisols. Even though pastures are found there, their management is very difficult and beef production remains very poor.

Vertisols in Costa Rica originate mostly from rhyolitic tufts high in biotitic micas, with some recent additions of very fine volcanic ash. The confluence of several factors is necessary for Vertisols to form: the presence of a depressional zone, which prevents a good drainage; the occurrence of materials rich in Si, Ca, and Mg that accumulate in al-

Vertisols are potentially quite fertile soils, with high pH,
Ca, and Mg contents. When organic matter is provided, favorable conditions for nutrient release may result. Thus, the constraints for high productivity on Vertisols are mainly physical rather than nutritional. Nevertheless there are many nutritional problems that get in the way of its high potential fertility being expressed by high plant growth. Organic matter additions under flooding conditions may induce the reduction of Fe and Mn to toxic levels for most crops. The high Ca and Mg concentrations generate additional problems leading to difficult uptake of other nutrients by plants, and hence poor plant growth, especially when the K content is low. Even though Ca phosphate complexes are the most soluble among all phosphates, a plant’s ability to use P is limited owing to its binding to Ca. Additionally, the content of minor cations is low in response to the high pH. All of these lead to serious limitations on plant growth.

The basic nutrient management strategy for Vertisols is maintenance fertilization with particular consideration of the levels of K and Zn (Sancho et al. 1984). Sulfur fertilization may also be useful (Bornemisza 1990). The 2:1 clays display a high cation retention capacity, especially for K and NH₄, on both the external and the internal surfaces, resulting in peculiar behaviors of these cations. To reduce K-induced deficiencies, this element needs to be applied, particularly for annual crops. The use of pesticides must be planned carefully when crop rotation is practiced since the active ingredients can be trapped in clay particles during the first culture cycle to be released later when irrigation is applied during the second cycle. Irrigation of Vertisols in Costa Rica will be possible soon because of the hydropower plant projects taking place in Guanacaste Province. Significant investments in infrastructure, such as canals, need to be done in order to achieve a sustainable and profitable use of such irrigation. Research and technology adaptation
programs are needed to ensure, for example, that the expandable clays will not destroy the new infrastructure.

**Alfisols and Ultisols**

The oldest and most weathered soils of Costa Rica belong to these orders, the differences being chemical and found in the subhorizon. Alfisols have more basic subhorizons and, particularly in Costa Rica, occur in dryer environments. In agronomic terms, both types of soils have a very similar “plow layer.” The real differences arise after intensive use, when Ultisols start exhibiting more marked fertility problems. In Costa Rica, these soils occupy a large area: about 31 percent of the territory (21 percent Ultisols, 10 percent Alfisols). In other times, and in other regions of the tropics today, the prevalent land use for these soils was slash-and-burn agriculture.

This is not relevant in Costa Rica today because of the high input agricultural system, the wet climatic conditions where natural vegetation cannot be burned, and the high quality requirements for agricultural products. In general, they are considered marginal for contemporary agriculture because of their low and rapidly declining fertility, and only some of them are in use, particularly for roots, tubers, and pineapple. During the beef cattle boom of the 1970s, these soils were most preferred for grazing purposes. However, the cattle degraded these soils rapidly. Most of these pastures were abandoned, leading to abandoned grasslands, secondary shrublands, and, eventually, to secondary forests.

These soils, however, have some good functions when properly managed. Virtually all the pineapple produced in Costa Rica is grown on these soils, as well as significant amounts of citrus, mango, avocado, palm heart (palmito), sugarcane, roots and tubers, etc. In the Southern Pacific region, large coffee plantations and Gmelina arborea plantations for pulp production are being established, although when excessive, increases erosion by favoring clay deflocculation. Such effects influence productivity much more drastically in Ultisols than Alfisols.

Boreal and Alfa soils have been successfully established, along with small coffee plantations. Alfisols also occur in the Central Pacific Zone in Grecia, Atenas, Orotina, and San Mateo districts, where small-scale fruit plantations (mango, tamarind, cashew, caimito) and recreational villas are the main forms of land use. Wherever they are found, these soils occupy the highest positions in the watersheds and along the slopes; that is, Alfisols are not subject to frequent addition of fresh materials and/or, are exposed to mild leaching conditions with consequent base accumulation at the subsoil (Fig.4.6).

These soils originate from the downward flow of water through the soil profile over long periods of time, under high temperature conditions and from practically any parent material. Their main feature is the presence of an argillic clay horizon formed from the water-borne migration of clay particles from the superficial horizons to the deepest layers of the soil. For this movement to occur, precipitation must be higher than potential evapotranspiration under free-drainage conditions, that is, the water table must extend very deep into the soil and be separated from the surface. This process involves the loss of Na, K, Ca, and Mg from the soil profile, leaving behind high concentrations of Al, Fe, and Si (tri and tetravalent cations) in greater extent in Ultisols than Alfisols.

The high concentration of hydrated iron accounts for the reddish color of these soils. More specifically, they are brownish red to reddish in the concave parts of the relief and brownish yellow to yellow in the convex depressions when Fe is bound with water molecules. The most relevant criterion considered for classification of Ultisols and Alfisols is the presence of an argillic and/or kandic subsurface horizon, which is acid in Ultisols (humid tropics) and neutral or basic in Alfisols (dry/humid tropics).

Kaolinites (1:1 clays) as well as Fe and Al oxides predominate in these soils (Alvarado et al. 2014b). Even when composed of fine materials, the formation of H bonds in 1:1 clays fosters particle aggregation and, therefore, a more developed structure. As these aggregates get coated by oxides, they are considered a larger particle known as “pseudosand” is formed. In some regions, Fe and Al accumulation is so high as to allow their exploitation as bauxite. Such deposits, also known as plinthe, display a white mottled surface over a red matrix in which gibbsite can be found.

The presence of stable aggregates in granular structures gives these soils excellent physical properties for agriculture, especially with respect to drainage. Overgrazing and intensive mechanization, however, can deteriorate their favorable physical properties irreversibly. Liming improves fertility, but when excessive, increases erosion by favoring clay deflocculation. Such effects influence productivity much more drastically in Ultisols, because of their low fertility. Unfor-
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Fortunately the good aggregation qualities of these soils also result in ideal conditions for nutrient losses, especially bases (Ca, Mg, K). This in turn, brings about severe acidity problems, including toxicity caused by Al and to a lesser extent Mn, and P availability problems due to its fixation on Fe and Al oxides and hydroxides surfaces. The rapid leaching also results in poor Effective Cation Exchange Capacity (ECEC) owing to a restricted specific surface of clay particle aggregation. Because no favorable conditions for organic matter accumulation are present, nitrates are easily lost by leaching and N availability is always limited. Leaching of micronutrients due to acidity results in deficiencies more commonly observed in even older soils highly exposed to run-off. All of these properties in turn account for the low fertility of Alfisols and especially Ultisols. The priority in managing these soils is replacing the lost Ca and Mg by liming, along with the selection of acid tolerant germplasm.

Agriculture is possible in these soils with an intense and well-balanced N-P-K fertilization program if an adequate supply of minor elements is included. The use of organic fertilizers, along with liming, can be an important source of nutrients while at the same time improving the physical properties altered by soil mismanagement.

Environmental Relationships between Soils, Litter, and Organisms

Soil as a Habitat

Many different types of animals live in and around the soil, leaving imprints in soil formation, nutrient recycling, and environmental biodegradation of organic residues (including pesticides), which have long been reported in tropical environments. Among the types of effects that animals...
leave in the soil, secretion of binding substances, burrows, and soil particle transportation (including organic matter/plant residues, clay, silt and sand particles), are mostly mentioned. Earthworms, termites, and ants are most visible, but other animals, like rodents, birds, and crabs, contribute to mixing soil material in specific environments as well. There is a group of animals that just live on the soil, causing little effect on its properties, including snails, snakes, and deer (Fig. 4.7). The various ways animals affect soil properties vary among them, mainly because of their size and number in the soils. The following sections intend to document these effects on Costa Rican soils.

Bacteria and Fungi

Bacteria and fungi in soil and soil litter are the most abundant organisms. From the agricultural perspective most of these microorganisms are harmful and well-studied, particularly when they turn into diseases for agricultural crops. Here, we describe several free N-fixing microorganisms and their host plants: *Rhizobium/Phaseolus leguminosarum* (bean), *Rhizobium/Erythrina* (poró), and *Frankia/Alnus acuminata* (alder). Mycorrhizae are discussed when related to forestry species (Fig. 4.8). Numerous publications address the beneficial effects of *Rhizobium* to the production of common *Phaseolus* beans, as well as the various soil properties that negatively affect the symbiotic relationship between the two partners (Ramírez and Alexander 1980a,b, Araya et al. 1986, Uribe et al. 1990, Acuña and Ramírez 1992a, Uribe 1993a,b, Castro et al. 1993, Acuña and Uribe 1996); similarly other studies emphasize the relationship between *Rhizobium/Glycine max* (Acuña and Ramírez 1992b, Acuña et al. 1987, Ortiz et al. 1986, 1990), and others explain the relationship *Rhizobium/Erythrina*
The symbiosis between Frankia and A. acuminata is also documented in various papers (Álvarez 1956, Russo 1989, Meza 1994, Segura et al. 2006). In the case of the mycorrhizae the available information mainly discusses the effects of its interaction with seedlings and trees in forestry nurseries and forest plantations (Vega 1964, Rojas 1992, Gadea et al. 2004, Alvarado et al. 2004).

Nematodes

Most nematodes are plant-parasitic species (e.g., see López and Salazar 1987), although a few free living nematodes exist in Costa Rica (Zullini et al. 2002). Various authors describe how soil texture, humidity, cation exchange capacity, pH, and organic matter content affect nematode population dynamics, directly and indirectly, by affecting the growth of living vegetation. In general, plant-parasitic nematode populations decrease with soil depth owing to a reduction in root biomass in the least aerated subsoil horizons; this has been proven for Meloidogyne incognita and Rotylenchulus reniformis on papaya plantations (Jiménez and López 1987), and rice fields all over Costa Rica (López and Salazar 1987, López 1988), with the exception of Longidorus sp. and Criconemella palustris. However, the population of nematodes depends to a major degree on the parasitic species they feed upon (López 1981), the crop phenology (Esquivel 1994), and the crop distribution in the field (Meneses et al. 2003). In order to control nematodes
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in banana plantations, nematicides were used in the past, causing human infertility to employees spraying the chemical, as reported by Ramírez and Ramírez (1980).

Arthropods

McGlynn et al. (2007) tested the effects of soil and litter nutrient stoichiometry on the invertebrate litter fauna of a Costa Rican tropical rain forest. Animal densities were estimated from 15 sites across a phosphorus gradient. The density of the invertebrate litter fauna varied, and was strongly tied to soil and litter phosphorus concentrations. An increase in phosphorus concentration corresponded with an equally proportionate increase in animal densities. Natural variation in nutrient levels can thus serve as a predictor of density in a highly diverse tropical animal community. Haggard and Ewel (1994) found that on fertile soils in the humid lowlands at La Selva Biological Station, phosphorus is abundant and preliminary data indicate that much of the organically bound P is under microbial control. Under the dry-wet climatic conditions of the Central Valley of Costa Rica, Herrera and Fournier (1977) and Fraile and Serafino (1978) found that soil and litter moisture availability plays an important role in determining the density and vertical distribution of soil microarthropods; Collembola, Protura, Symphyla, and Acarina were those most adversely affected by rainfall, while Coccioidea and other groups were unaffected by it (Fraile and Serafino 1978). Also, the invertebrate population was more diverse and stable in the oldest forest, but populations increased when litter moisture content increased with the first rains (Herrera and Fournier 1977). Populations of arthropods decrease with elevation above sea level (Bruhl et al.1999). Atkin and Proctor (1988) studied the litter and soil fauna in1 ha plots at six altitudes along a transect ranging from 100 to 2,600 m a.s.l. on the Caribbean slope of Barva Volcano. They showed that the invertebrate biomass in soils at 100 and 500 m a.s.l. seem to be the highest ever recorded for tropical rainforests. This is partially attributed to the presence of a clear soil temperature gradient (Fig.4.9).

Springtails

Guillén et al. (2006a) studied the diversity and abundance of soil springtails (Collembola) in a primary forest, a secondary forest, and a coffee plantation, in Tapanti National Park. Each month, eight soil samples were taken in each ecosystem, totaling 360 samples. A total of 23,751 springtails were found, belonging to 9 families and 16 species. Of the three ecosystems, the primary forest was the most diverse (H' = 2.406), followed by the secondary forest (H' = 2.174), and the coffee plantation presented the lowest diversity (H' = 1.651). In contrast with diversity, the greatest abundance of springtails was found in the coffee plantation with 10,111 individuals. Guillén, Soto, and Springer (2006b) also found that the largest springtail biomass is associated with the highest organic matter content, lower penetration resistance, and lower pH values of the primary forest. The results showed an association between these variables and some collembolan species, which indicates that changes in the structure of collembolan communities can be used as biological indicators of soil quality and management of ecosystems.

Ants and Termites

In Costa Rica, 85 genera and at least 620 species of ant have been identified so far (Longino and Hanson 1995,
However, the number of genera and species present in different agroecosystems varies between 9–16 genera and 13–23 species in coffee plantations (Benítez and Perfecto 1989, Perfecto and Vandermeer 1994, Barbera 2001), and 10–19 genera and 16–26 species in cacao plantations (Young 1986). The influence of some of these species on Costa Rican soil properties is also being recognized. Araya and Alvarado (1978) and Araya (1980) determined the influence of leaf-cutter ants (Atta cephalotes) on the chemical and morphological properties of soil of the Premontane Wet forest (Fabio Baudrit Experimental Station), the Premontane Wet forest transition to lowland (Santa Rosa National Park), and the Tropical Wet forest transition to per-humid conditions (La Lola farm). Results show that vertical translocation of materials from the upper to the lower soil horizons and vice versa is large, and varies in different ecosystems; values of cation exchange capacity in ant-affected and undisturbed soil were 30 and 50 cmol(+)/100g−1, respectively, while Ca, Mg, and K contents were 2 and 23, 1 and 28, and 0.36 and 1.6 cmol(+)/100g−1, respectively. Other soil properties, like organic matter content, available P, pH, and sand, silt, and clay content, were also affected significantly. 

Alvarado et al. (1981) studied the influence of leaf-cutter ants (A. cephalotes) on the morphology of twenty-seven soil profiles of Andisols distributed within a 2.5-ha site in Turrialba, Costa Rica. Leaf-cutter ant influence on each profile was noted in 85% of the soil profiles or pedons. The influence on each profile was estimated, and out of all profiles, 37% had low, 26% medium, and 22% high disturbance. The surface area covered by leaf-cutter mounds was 38.9% of the study area; only 1% of the aboveground disturbed area was active, however. Leaf-cutter ants transport material from the AB and B horizons to the soil surface, producing a new A1 horizon. In addition, some subsoil chambers are filled with plant material. Knowledge of termites that are active at soil level is still scanty, however (Fig. 4.10).

The E. biolleyi population density was 0.25 individuals m−2, and no clear-cut trends in associated flora and fauna were found but the animals preferred rotten to non-rotten wood, and water-soaked soil to oven-dried soil, during periods of inactivity.

Earthworms

The knowledge of soil-born native earthworm species of Costa Rica is limited. Esquivel (1997) found no relationship between density of earthworms and different agroecosystem properties in the wet humid lowlands of the Atlantic Zone; the author found an average of 194 individuals m−2, with Pontoscolex corethrurus being the dominant species owing to its high adaptability to disturbed ecosystems. López and Kass (1996) found that Erythrina mulch and mucuna green manure treatments resulted in better phosphorus balances and higher earthworm populations and increased the yield of common bean (Phaseolus vulgaris). While sampling earthworm communities at eight sites of the Caribbean Coast to assess the distribution of the peregrine pantropical species P. corethrurus and its
relationships with native species depending on the type of land use, Lapied and Lavelle (2003) found that this species is largely dominant in almost all habitat types with a density range of 143 to 182 individuals m$^{-2}$. The species became dominant even in remaining plots of primary forests. In contrast, the species has not yet penetrated the large primary forest of the northeast of the country, where only native species could be found, and reached a maximum density of ca. 361 individuals m$^{-2}$ in banana plantation sites. In all sites, a density increase of this species corresponds significantly with a reduction of the rest of the earthworm fauna except for *Dichogaster* sp. Where *P. corethrurus* was absent, density of other species reached 34.4 individuals m$^{-2}$.

In southern Costa Rica, human immigration and sustained activities probably favored the establishment of *P. corethrurus*. León, Bolaños, and Fraile (1993) studied the relationship between edaphic conditions and the abundance and biomass of earthworms at eight sites in Costa Rica where organic waste accumulates, finding that the abundance and the biomass of *P. corethrurus* follows models that depend on soil carbon percentages (Fig.4.11).

**Crabs**

The land crab *Gecarcinus quadratus* (Gecarcinidae) lives in densities exceeding 10,000 adults ha$^{-1}$ in the coastal forests of Corcovado National Park, Costa Rica (Fig.4.12). Crabs, living solitarily in half-meter deep burrows, forage nocturnally, transporting plant propagules and fallen leaves to subterranean chambers. The influence of *G. quadratus* on the distribution of soil organic carbon and root distribution in a Costa Rican rain forest was studied by Sherman (2006). Percent organic carbon in the crabzone (CZ) soils decreased with depth. The carbonless zone (CLZ) soils contained significantly more carbon at the topsoil and 32 cm depths but significantly less carbon at 72 cm. Carbon values at these depths, however, differed in regards to season. Vertical root profiles taken from the adjacent zones all indicated greater densities at the surface soils than below. The CZ had relatively lower root densities in the top 15 cm of the soil than the nearby CLZ. Surface densities of very fine and fine roots were 50% and 72% lower in the CZ than in the CLZ respectively.

**Rodents**

Many rodent species spend their lives in and around the soil, where they mix large amounts of material while digging the ground to build their nests and tunnels. According to Reid (1997) rodents of Costa Rica include 2 suborders, 8 families, and 48 species. Among the families, 33 species of rats and mice are most abundant in soil ecosystems. They belong to the families Muridae, Heteromyidae, and Echimyidae; the remaining rodents belong to Sciuridae (5 species of squirrels), Geomyidae (4 species of pocket gophers or *taltuzas*), and one species each in the Erethizontidae (porcupine), Dasyproctidae (*guatusa*), and Agoutidae (agouti, *tepezcuintle*) (Fig.4.13).

Rodents can be grouped by size, according to Javier Monge (University of Costa Rica, pers. comm.), as follows: (1) large rodents (>2 kg/adult) such as the agouti or *tepezcuintle* (*Agouti paca*), the guatusa (*Dasyprocta punctata*), and the porcupine (*Coendou mexicanus*); (2) medium-sized rodents (0.1–1 kg/adult), including squirrels (*Sciuridae*), *taltuzas* (*Geomyidae*), and large rats (*Echimyidae*), and (3) small rodents (<0.1 kg/adult) that includes other rats and mice.
Chapter 4

(Muridae and Heteromyidae). The pocket gophers occupy many ecological niches, except those with clayey soils. To give an idea of the amount of soil material reworked by this species: their nesting chamber might be up to 60 x 110 x 30 cm in width, length, and height, respectively; their tunnels can be as long as 192 m but average values lie between 30–80 m, disturbing an area of around 200–325 m² per individual (Monge 2006). According to Rodríguez and Vaughan (1985), a female agouti (D. punctata) has a home range of 3.9 ha, and maximum and minimum distances travelled daily reach 1,800 and 727 m, respectively. When roaming around in the La Selva tropical rain forest, agoutis not only mix soil materials but also help transport Carapa guianensis seeds (Arias 2001). The species is also the main secondary disperser of large seeds in the cloud forest of Monteverde (Wenny 2002).

Cattle

In the dry tropical ecosystems of Guanacaste, various authors have found that cattle grazing: (1) improves seed
dispersion via excreta of *Enterolobium cyclocarpum* and *Crescentia alata* (Janzen 1982a, b, Alvarado et al. 1982), (2) increases soil P availability, (3) reduces bulk density under dung droppings from 1.05 to 0.93 g cm⁻³, (4) increases soil porosity from 13 to 21% (Herrick and Lal 1995, 1996), and (5) decreases aboveground residue accumulation, thus reducing fire frequency in dry tropical environments (Barbosa 1994). Changes in chemical properties of the soils are not as clear (Daubenmire 1972, Johnson and Wedin 1997). While evaluating the compaction and compactability of agricultural and cattle-raisinig soils in Guanacaste, Agüero and Alvarado (1983) found in cattle areas compaction average values of 62 kg cm⁻², values that doubled the ones found in cropping lands (average 30 kg cm⁻²). These effects on the soil physical characteristics delay the regeneration of natural forest. The effect of cattle dung on the physical properties of the dry tropical pasture lands of Guanacaste was studied by Herrick and Lal (1995, 1996); these authors found an increase of soil porosity from 13 to 21% in the soil without dung, and under dung additions, respectively (Fig. 4.14).

**Soils and Vegetation**

As previously stated, to a certain extent soils can help determine the best land use. However, land use naturally affects soil properties, effects enhanced by human activities. As an example, the distribution of the cloud forest (wet tropical montane forest) and páramo vegetation at Cerro de la Muerte and Cerro Chirripó is associated with climatic and edaphic altitudinal gradients (Kappelle and van Uffenen 2005, 2006, Kappelle and Horn, chapter 15 of this volume). Inversely, in the same region, Blaser and Camacho (1990) described the occurrence of two types of soils developed from volcanic ash under different vegetation cover. Below the cover of mixed oak forest (*Chusquea talamancensis*, *Quercus costaricensis*, *Grammadenia myricoides*, *Prunus cornifolia*, and *Vaccinium consanguineum*), Placudands are dominant. However, below the white oak forest cover (*Chusquea tomentosa*, *Ardisia glandulosa-marginata*, *Quercus copeyensis*, *Weinmannia pinnata*, *Ocotea spp.*, *Nectandra* spp., *Styrax argenteus*, and *Ilex* spp.), Dys-trudands are dominant. The difference between the two soils is considerable, since Placudands present a thin hard layer of iron known as “placic horizon” formed by preferential movement of Fe, chelated by organic substances produced under the specific oak trees, thus impeding good drainage.

Among the various reasons explaining shifting cultivation in tropical environments, Sánchez (1985) mentions soil fertility decline, weed invasion, and the impact of insects and diseases on crop yield over time. The issue of soil fertility decline is strongly related to low-input agricultural systems, and usually associated with soil organic matter depletion, nutrient leaching and retention in highly weathered soils, and nutrient extraction via agricultural and forestry products (Hartemink 2003). Recently, studies on soil carbon sequestration tend to provide an alternative to identify proper land uses, with the purpose of recycling residues, planting crops that enhance soil organic matter accumulation, and applying environmentally friendly soil practices (Lal et al. 2006). The next paragraphs describe the main factors that affect Soil Organic Matter (SOM) in Costa Rica.
Chapter 4

Soil Organic Matter

Differences in Soil Organic Matter (SOM) by Life Zone

Data collected by Alvarado (2006) show that Soil Organic Matter (SOM) content in Costa Rica increases from the tropical (warm) to the montane (cool) belt, both in the topsoil and subsoil (Table 4.1). The amount of residues added to the ecosystem in natural forests of Costa Rica decreases with altitude above sea level (Heaney and Proctor, 1989), 9.0, 6.6, 5.8, and 5.3 t ha⁻¹ year⁻¹ at elevations of 100, 1,000, 2,000, and 2,600 m a.s.l., respectively. This is due to lower photosynthesis rates and exposition of vegetation to strong winds. However, the accumulation of residues under cool mountainous weather ecosystems is explained in terms of having low N content (Heaney and Proctor, 1989), being hard and waxy (Holdridge et al., 1971), containing high amounts of phenols (Montagnini and Jordan, 2002), and having a low population of arthropods (Bruhl et al., 1999), all of them contributing to a reduction of residues’ mineralization rates (Tanner et al., 1998). Powers and Schlesinger (2002a) also attribute this accumulation to the occurrence of amorphous clay minerals in mid-elevation Andisols in Costa Rica. These minerals make it difficult for organic materials to easily decompose.

As precipitation increases along vegetation gradients, soil organic matter increases, although the effect of temperature is more acute than that of moisture. Residue in lowland humid tropical forests undergoes a fast and efficient recycling process, hence its short life span in the ecosystem (Montagnini, 2002). In tropical forests, the production of residue increases with average annual rainfall (Bernhard and Loumeto, 2002) and its accumulation lasts only for the length of the dry season period.

On the basis of Holdridge’s Life Zone distribution and area (ha) in Costa Rica, a total of 1,348.2 Tg of SOM was calculated for the country (Table 4.2). The life zones that contribute the most to SOM in Costa Rica are Premontane Wet Forest (391.0 Tg), Tropical Moist Forest (203.2 Tg), and Premontane Moist Forest (172.9 Tg), respectively.

Differences in Soil Organic Matter (SOM) by Soil Type

Small areas of peat deposits (Histisols) have been found in Costa Rica as the following: (1) thin blanket deposits about 1 m thick in the highlands of the Talamanca Range (e.g., at La Chonta close to El Empalme along the Inter-American Highway), such as in Sphagnofibristes (Kappelle and van Uffelen, 2005), (2) peat layers interbedded with alluvium layers

Table 4.1. Soil Organic Matter (SOM %a) Content as Related to Holdridge’s Life Zones in Costa Rica

<table>
<thead>
<tr>
<th>Life Zone</th>
<th>Dry</th>
<th>Moist</th>
<th>Wet</th>
<th>Rain forest</th>
<th>AVERAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical</td>
<td>3.3/1.0 (7)</td>
<td>3.0/0.9 (7)</td>
<td>4.3/1.3 (13)</td>
<td>6.6/2.0 (5)</td>
<td>3.6/1.1 (27)</td>
</tr>
<tr>
<td>Premontane</td>
<td>6.3/2.8 (2)</td>
<td>6.9/2.0 (6)</td>
<td>6.6/2.20 (6)</td>
<td>6.6/2.3 (13)</td>
<td></td>
</tr>
<tr>
<td>L. Montane</td>
<td>4.9/1.6 (1)</td>
<td>19.1/4.9 (1)</td>
<td>20.4/6.7 (3)</td>
<td>14.8/4.4 (5)</td>
<td></td>
</tr>
<tr>
<td>Montane</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19.8/Rock (1)</td>
</tr>
<tr>
<td>AVERAGE</td>
<td>3.3/1.0 (7)</td>
<td>4.8/1.8 (10)</td>
<td>10.1/2.8 (20)</td>
<td>15.6/4.3 (9)</td>
<td></td>
</tr>
</tbody>
</table>

a SOM (0–0.30 m) / SOM (0.31 – 1.00 m) (Number of samples).

Source: Alvarado 2006.

Table 4.2. Soil Organic Matter (SOM) Stock in Costa Rica Calculated by Holdridge’s Life Zones

<table>
<thead>
<tr>
<th>LIFE ZONE (LZ)</th>
<th>Extension (Ha x 1,000)</th>
<th>Mg SOM to a depth of (m) x = 0.3</th>
<th>y = 1</th>
<th>SOM / LZ (Tg)</th>
<th>No. of samples</th>
<th>Regression equation</th>
<th>Regression coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical dry forest</td>
<td>150.3</td>
<td>82.7</td>
<td>142.9</td>
<td>21.5</td>
<td>7</td>
<td>$y = 1.2697x + 37.852$</td>
<td>0.955</td>
</tr>
<tr>
<td>Tropical moist forest</td>
<td>1,058.2</td>
<td>119.9</td>
<td>192.0</td>
<td>203.2</td>
<td>7</td>
<td>$y = 1.4993x + 49.034$</td>
<td>0.5945</td>
</tr>
<tr>
<td>Tropical wet forest</td>
<td>1,083.6</td>
<td>86.9</td>
<td>144.4</td>
<td>156.5</td>
<td>13</td>
<td>$y = 1.1008x + 4.7945$</td>
<td>0.9127</td>
</tr>
<tr>
<td>Premontane moist forest</td>
<td>556.7</td>
<td>193.5</td>
<td>310.5</td>
<td>172.9</td>
<td>2</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Premontane wet forest</td>
<td>1,217.7</td>
<td>191.6</td>
<td>321.1</td>
<td>391.0</td>
<td>6</td>
<td>$y = 2.6939x – 59.582$</td>
<td>0.9598</td>
</tr>
<tr>
<td>Premontane rain forest</td>
<td>445.3</td>
<td>86.1</td>
<td>291.2</td>
<td>129.7</td>
<td>5</td>
<td>$y = 6.283x – 249.47$</td>
<td>0.9803</td>
</tr>
<tr>
<td>Lower montane rain forest</td>
<td>137.6</td>
<td>309.6</td>
<td>586.2</td>
<td>80.7</td>
<td>3</td>
<td>$y = 1.7414x + 220.37$</td>
<td>0.9994</td>
</tr>
<tr>
<td>Montane moist forest</td>
<td>335.5</td>
<td>188.2</td>
<td>342.0</td>
<td>114.7</td>
<td>1</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Montane wet forest</td>
<td>1.9</td>
<td>228.3</td>
<td>420.8</td>
<td>0.8</td>
<td>1</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Montane rain forest</td>
<td>118.7</td>
<td>244.3</td>
<td>651.6</td>
<td>77.3</td>
<td>6</td>
<td>$y = 1.4338x – 24.441$</td>
<td>0.9372</td>
</tr>
<tr>
<td>COSTA RICA</td>
<td>5,105.6</td>
<td>1348.2</td>
<td>51</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTE: nd = no data are available.

Source: Alvarado 2006.
Soils of Costa Rica

Table 4.3. Soil Organic Matter (SOM %) Content in 100 Samples of Vertisols, Inceptisols, Ultisols, and Andisols (25 A Horizons of Each Order) from Costa Rica

<table>
<thead>
<tr>
<th>Soil Order</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertisols</td>
<td>1.6</td>
<td>5.9</td>
<td>3.5</td>
</tr>
<tr>
<td>Inceptisols</td>
<td>1.0</td>
<td>9.9</td>
<td>4.2</td>
</tr>
<tr>
<td>Ultisols</td>
<td>1.9</td>
<td>9.7</td>
<td>5.7</td>
</tr>
<tr>
<td>Andisols</td>
<td>4.8</td>
<td>24.0</td>
<td>10.9</td>
</tr>
</tbody>
</table>

Adapted from Cabalceta 1993.

Table 4.4. Soil Organic Matter (SOM) in Costa Rica Calculated by Soil Order

<table>
<thead>
<tr>
<th>SOIL ORDER (SO)</th>
<th>Extension (Ha x 1,000)</th>
<th>Mg SOM to a depth of (m)</th>
<th>SOM / SO (Tg)</th>
<th>No. of samples</th>
<th>Regression equation</th>
<th>Regression coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x = 0.3</td>
<td>y = 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inceptisols</td>
<td>1,976.0</td>
<td>127.5</td>
<td>249.4</td>
<td>492.8</td>
<td>27</td>
<td>y = 2.1565x − 17.388</td>
</tr>
<tr>
<td>Ultisols</td>
<td>1,069.0</td>
<td>138.4</td>
<td>244.6</td>
<td>261.5</td>
<td>15</td>
<td>y = 2.0729x − 42.378</td>
</tr>
<tr>
<td>Andisols</td>
<td>750.0</td>
<td>222.0</td>
<td>401.8</td>
<td>301.3</td>
<td>14</td>
<td>y = 1.8351x − 5.6576</td>
</tr>
<tr>
<td>Entisols</td>
<td>627.0</td>
<td>116.7</td>
<td>286.1</td>
<td>179.4</td>
<td>14</td>
<td>y = 1.3424x + 129.44</td>
</tr>
<tr>
<td>Alfisols</td>
<td>487.2</td>
<td>156.7</td>
<td>260.7</td>
<td>127.0</td>
<td>8</td>
<td>y = 1.4003x + 41.212</td>
</tr>
<tr>
<td>Vertisols</td>
<td>78.4</td>
<td>111.2</td>
<td>223.8</td>
<td>17.6</td>
<td>20</td>
<td>y = 1.6993x + 34.82</td>
</tr>
<tr>
<td>Mollisols</td>
<td>69.0</td>
<td>144.0</td>
<td>269.2</td>
<td>18.6</td>
<td>16</td>
<td>y = 1.8974x − 4.1355</td>
</tr>
<tr>
<td>Histosols</td>
<td>49.3</td>
<td>362.6</td>
<td>967.3</td>
<td>47.7</td>
<td>3</td>
<td>y = 8.2793x − 2035.1</td>
</tr>
</tbody>
</table>

Source: Alvarado 2006.

A study conducted in Costa Rica by Cabalceta (1993) to evaluate different methods for extracting soil-available nutrients also included SOM determinations as a part of the soils’ characterization. In this study, 25 topsoils of each of the 4 major soil orders of the country were sampled, and results are presented in Table 4.3. The author reported a sequence for SOM content in the A soil horizon, in the following order: Vertisols < Inceptisols < Ultisols < Andisols. It is noteworthy that the larger the average of SOM of a particular soil order, the larger the range of its Soil Organic Content (SOC) is.

Under natural conditions, the sequestration of SOC in each soil order can be increased up to the maximum value of its range. However, unpublished results in organic farming systems show that in spite of the large amounts of compost or organic residues applied (10–30 Mg/ha), the total amount of C in soils rarely increases. According to Schlesinger (2000), only a small sink for SOC in soils may derive from the adoption of conservation tillage and the regrowth of native vegetation on abandoned agricultural land, but no net sink for SOC is likely to occur through application of manure to agricultural lands.

Soil organic matter contents for the country calculated by soil order (Alvarado 2006), came to a total of 1,445.7 Tg (Table 4.4), which is in fact a larger amount than found when using the Life Zone approach (Table 4.2), though within reasonable assumptions. SOM depends on soil order, reflecting their genesis: Entisols < Ultisols = Inceptisols < Mollisols = Alfisols < Andisols < Histisols. However, the soil orders that contribute most (owing to the size of the area they cover) were Inceptisols (492.8 Tg), Andisols (301.3 Tg), and Ultisols (261.5 Tg), respectively. In this case, correlations between SOM at 0.3 m vs. 1.0 m depth for each order were quite significant, with the exception of Entisols.

Soil Organic Matter (SOM) Turnover

Sauerbeck and González’ (1977) study on the decomposition of 14C-labeled wheat (Triticum aestivum) straw in 12 representative soils of Costa Rica showed that, under field conditions, after one year, 23 to 36% of the 14C added in the wheat straw remained in the soil. However, four years later the residual 14C ranged from 11 to 23%. The asymptotic model best fitted the turnover of the residues. Similar results were obtained while describing the turnover of banana (Musa spp.) (Vargas and Flores 1995) and peach palm (Bactris gasipaes) fresh residues under field conditions (Soto et al. 2002) using decomposition litterbags. In these studies, fruits were harvested on a weekly basis, applying residues after each harvest. A linear model that relates to different stages of decomposed residues, like the one proposed in Heal et al. (1997), is more appropriate.
Other decomposition studies, using rain forest species residues, show similar results (Babbar and Ewel 1989, Byard et al. 1996). Land management practices such as fire, grazing, tillage, and fertilizer application, among others, affect the distribution or SOC (Townsend et al. 2002). The accumulation of SOC underground is strongly related to the following: (1) fine roots decomposing naturally (humification) in the soil; (2) self-pruning of root during dry season in deciduous species (Ordóñez 2003); (3) root chopping by plowing the land (Veldkamp 1994); (4) root decay after pruning the crop (coffee); and (5) decay of microorganism’s biomass. A special case of C build-up in the soil is that of so-called black carbon. This fraction is the result of burning lands for cropping purposes, and often due to common savannah and forest fires that may convert up to 2% of the standing biomass into charred material. Char production due to burning of deciduous wood is normally higher; at the same time, the char fraction in soils may last for long periods.

Soil Organic Matter (SOM) and Ecosystem Management

According to Gichuru et al. (2003), alteration of forest cover due to human intervention ranges from marginal modification to fundamental transformation; selective extraction of wood represents one extreme, while deforestation represents the opposite. After deforestation, land use changes will have a profound influence on soil properties (i.e., organic matter content and bulk density), since both the residue addition and decomposition rates are considerably affected (Ewel et al. 1981, Raich 1983, Veldkamp 1994, Johnson and Wedin 1997, Guggenberger and Zech 1999, Powers 2001, 2004, Powers and Schlesinger 2002a, b).

The recovery of C in the deeper layers of Andisols is higher than that of the A soil horizons, which is related to a lower presence of plant residues with increased depth and to an accumulation of fulvic acids in these layers (Alvarado 1974). Van Dam et al. (1997) observed that decomposition rates decrease strongly with depth and that diffusional transport alone is insufficient for the simulation of SOC movements into the soil; it had to be augmented by depth-dependent decomposition rates to explain the dynamics of SOC, delta $^{13}$C, and delta $^{14}$C. Cleveland et al. (2004) concluded that, with regards to the presence of physico-chemical reactions with soil surfaces, humic (hydrophobic) fractions of dissolved organic matter (DOM) become more abundant than non-humic (hydrophilic) fractions over time. The latter fraction is the one that migrates into deeper layers of soil profiles. Both Cleveland et al. (2004) and Powers and Schlesinger (2002b) reported that neither the changes in delta $^{13}$C isotopic fraction during DOM uptake by soil organisms, nor the difference in composition of litter and roots, explained the variation of delta $^{13}$C values with soil depth.

To evaluate the impact of the change in vegetation cover on soil properties, three different data types are used to assess soil changes: (1) expert knowledge, (2) nutrient balances, and (3) monitoring of soil properties over time (Hartemink 2003). Independently of how the impact was measured, available information should be used to reduce data variability and improve data interpretation, while looking at (1) ecological differences (e.g., dry vs. wet tropics, or Andisols vs. Ultisols), (2) the kind of a change in land use (e.g., forest to grassland vs. grassland to secondary forest), and (3) type of data collected (e.g., changes monitored over time in samples taken at one site or chronosequential sampling vs. changes estimated for samples taken in different adjacent land-use systems sampled at the same time and known as false-time series). The effect of the ecological impact on soil organic matter accumulation was covered in previous sections, while the impact of the change in vegetation cover will be discussed in the next paragraphs.

Changes in Soil Organic Content (SOC)

According to Veldkamp (1994) deforestation, followed by 25 years of pasture, caused a net loss of 21.8 Mg/ha of SOC for Eutric Hapludands and 1.5 Mg/ha for Oxic Humintrópept in the Atlantic lowlands of Costa Rica. In an Andic Humintrópept the author found that the decomposition of tree roots caused an extra input of SOC during the first year after deforestation and a strong stabilization of SOC by forming Al-organic matter complexes.

Similarly, slash and burning of a 8–9-yr-old evergreen forest around Turrialba, Costa Rica, volatilized 31% of the initial amount of SOC, 22% of N, and 49% of S. Soil CO$_2$ evolution was higher beneath an 11-week-old slash field (3.6 g/m$^2$ daily of C) than from beneath an evergreen forest (2.5 g/m$^2$), probably because slash conserved soil moisture better than actively transpiring forest (Ewel et al. 1981). Particle-sized separation of SOM, where particulate SOM (light fraction and sand-associated SOM) is separated from mineral-bond SOM (silt- and clay-bonded SOM) revealed that under agricultural use of a soil formerly under primary forest in the country’s northern lowland Huetar region, a depletion of the particulate SOM occurred, whereas clay- and silt-bond SOM was less affected (Guggenberger and Zech 1999).

These authors also observed that abandonment of pastures and growth of secondary forests raised SOC content
in all separates to a pre-cultivation level within 18 years, and sand-associated SOC was even higher compared with values for the primary forest. Results suggest that land use primarily influences the balance across the light fraction and the size separates, with the particulate SOM pool being the most significant component in the context of management impacts on these soils.

Powers (2001, 2004) looked for changes in total SOC concentration (Mg C/ha) at a depth of 0.30 cm that occur during different land-use transitions in northeastern Costa Rica. The study included 12 sites where old-growth forest was converted into banana plantations, 15 sites that suffered a conversion of pasture to cash crops, and four sites demonstrating the change of pastureland into Vochysia guatemalensis forest. At the sites converted to banana plantations, the top soil SOC concentration decreased from 37% to 16.5%. Similar results were obtained for sites where pastures were replaced by crops. However, sites with soils now under V. guatemalensis did not show an increase in SOC storage, at least not during the first decade. In conclusion, reduced C input to the soil may be a key reason that explains the loss of SOC pools during land-use changes in ecosystems replaced by pastures or crops, since SOC restoration rates appear to be slow.

To determine how the conversion in a Tropical Premontane Wet Forest and a nearby secondary forest affects the SOC budget, major soil C storages, inputs, and CO2 evolution from a tropical Inceptisol were measured by Raich (1983) over a six-month period. Total C storage in and on the mature forest soil comprised 9,330 g C m−2 in SOM, 1,850 g C m−2 in litter, and 340 g C m−2 in small roots (diameter of 5 mm); larger roots were not measured. Average daily inputs to the mature forest soil include 1.3 g C m−2 in litterfall and 0.10 g dissolved organic carbon (DOC) m−2 in precipitation (throughfall + stem flow). The evolution of CO2 from the mature forest averaged 3.4 g C m−2 d−1 or 2.6 times the average rate of litterfall. Total C storage in and on the secondary growth soil was composed of 8,600 g C m−2 in SOM, 700 g C m−2 in litter and 157 g C m−2 in small roots, or 2,060 g C m−2 less than in the mature forest. Average daily inputs to the mature forest soil include 0.7 g C m−2 in litterfall and 0.12 g DOC m−2 in precipitation (throughfall + stem flow). The evolution of CO2 from mature forest averaged 4.6 g C m−2 d−1 or 1.4 times the average rate in the mature forest. Measured inputs of C to soils were considerably less than soil-CO2 evolution rates at both sites.

Johnson and Wedin (1997) reported a loss of SOM in the Guanacaste region while comparing mature forest and grassland soils—an effect attributed to a larger rate of mineralization of residues due to higher temperatures in the later ecosystem. In a study to determine soil changes associated with the conversion of grasslands to 13-year-old and 17-year-old secondary forests in tropical dry forest of Guanacaste on Andic and Typic Haplusterts, Alfaro et al. (2001) found that plant cover did not affect SOM, pH, soil acidity, and K content; however, Ca and Mg contents were higher under the 13-year-old forest cover (nutrients associated to litter added to 7.03%) than the 17-year-old forest cover (nutrients associated to litter added to 4.51%). In the same environment, Leiva (2007) did not find any differences in SOC due to changes in vegetation cover after pasture abandonment in Entisols of the ignimbritic plateau of Guanacaste; however, the author found nutritional differences related to forest age (an initial decrease and a further increase of nutrient availability with forest age).

Oelbermann et al. (2004) mention that the potential to sequester C in aboveground components in agroforestry systems is estimated to be 2.1 × 109 Mg C year−1 in tropical and 1.9 × 109 Mg C year−1 in temperate biomes. Studies from Costa Rica have shown that a 10-year-old system with Erythrina poepiggiana sequestered C at a rate of 0.4 Mg C ha−1 year−1 in coarse roots and 0.3 Mg C ha−1 year−1 in tree trunks. Tree branches and leaves are added to the soil as mulch, contributing 1.4 Mg C ha−1 year−1 in addition to 3.0 Mg ha−1 year−1 from crop residues. This resulted in an annual increase of the SOC pool by 0.6 Mg ha−1 year−1. Oelbermann et al. (2005) quantified the C stock of tree roots and C input from tree prunings and crop residues in 19-, 10- and 4-year-old E. poepiggiana and Glyricidia sepium alley cropping systems in Costa Rica. The 19-year-old alley cropping system was studied at two fertilizer levels (tree prunings only [−N], and tree prunings plus chicken manure [+N]), and was compared with a sole crop. The 10- and 4-year-old systems were also studied at two fertilizer levels (tree prunings only [−A], and tree prunings plus Arachis pintoi as a groundcover [+A]), and compared with a sole crop. In the 19-year-old system C input from G. sepium was significantly greater compared with E. poepiggiana, but for both tree species there was no significant difference between +N and −N treatments. For the 10- and 4-year-old systems, E. poepiggiana had a significantly higher C input from prunings compared to G. sepium, and the presence of A. pintoi increased prunning biomass productivity significantly in these systems. Tree roots of 10- (4,527 kg C ha−1) and 4-year-old (3,667 kg C ha−1) E. poepiggiana represented 16 and 28% of the total C allocation. Carbon input from maize (Zea mays L.) and bean (Phaseolus vulgaris L.) residues were not significantly different between alley crops and sole crops in the 19-year-old system per unit of cropped land. In this system, +N treatments had
a significantly greater C input from bean residue than in 
-N treatments, but no such trend was observed for maize residues. Carbon input from maize and bean residues were 
significantly greater in alley crops than the sole crops, but 
not significantly different between +A and -A treatments in 
the younger system. The greatest input of organic material 
occurred in the 19-year-old alley crop followed by the 10- 
and 4-year-old alley crops.


Nutrient Availability

The soils of Costa Rica are, in overview, moderately fertile 
by global standards, but very fertile compared to other tropical 
conditions. The old soils of much of Africa and Amazonia 
were far more severe problems, but the young soils of 
Northern glaciated areas in the Midwest of the USA are 
much more fertile. According to Bertsch (1986), the most 
important chemical qualities of soils with respect to their 
nutritional value for plants relate to the abundance and 
availability of the major plant nutrients, nitrogen, phosphorus, 
and potassium (NPK). By these criteria specific tracks of 
land in Costa Rica present some problems for economic 
agricultural activities. As in other tropical areas, all Costa 
Rican soils are deficient in N. In addition, 74 percent are 
deficient in P, and 22 percent of the country is deficient in 
K. Ca and Mg are low in 35 percent of the soils, a problem 
considered more relevant than Al toxicity that occupied a 
larger area (20–30 percent). There is less information on 
micronutrients. Boron deficiency is probably most important, 
followed by Zn (26 percent) and Mn (23 percent). Very 
few parts of the country present Fe deficiencies (6 percent), 
and only some areas show Cu toxicity problems (Cordero 
and Ramirez 1979). All of these nutritionally related problems 
can easily be overcome with the use of soil amendments like lime and fertilizers.

More recent literature seems to be showing that the 
physical properties of soils can restrict agricultural activities 
at a national level. Most important are shallowness, steep 
relief, erosion susceptibility (see section 2.3), flooding risk, 
drought-inducing sandy textures or heavy textures (gener- 
ated by swamps), and compacted soils (Beets 1990). Animal 
nutrition as well as human can be influenced by the soils 
via mineral concentration in feeding material. The quantity of 
most nutrients in pasture soils and hence forages is ade-
quate (Bertsch 1986) except that 63 percent of soil pasture 
samples had insufficient levels of Co or Cu for ruminant 
In past years Costa Ricans have suffered from iodine de-
ficiency, a typical problem related to volcanic ash-derived 
soils. When salt was iodized this deficiency disappeared ex-
ccept for some remote coastal regions where people consume 
non-iodized salt.

Soil Compaction and Erosion

Land deterioration via soil compaction is reported by dif-
ferent authors in Costa Rica. An example of minor im-
 pact is presented by Radulovich and Sollins (1985) who 
described the effect of foot traffic at La Selva Biological 
Station where penetration resistance (kg cm⁻²) increased 
from 0.41 to 0.96, while bulk density increased from 0.63 
to 0.68. A major impact case is presented by Agüero and 
Alvarado (1983) who measured the effect of cattle tramp-
ing on grasslands in Guanacaste dry lowlands, finding 
penetration resistance (kg cm⁻²) values of 62 in cattle areas, 
a value that more than doubles the agricultural land average 
of 30. On the hillsides of the Poás Volcano, wood volume 
of 15-year-old plantations of Cedrela odorata decreased 
from 110 to 11 m³ ha⁻¹ and was associated with changes 
in soil bulk density between 0.96–1.12 and 1.18–1.34 g 
cm⁻³, respectively (Castaing 1982). In the same area but 
on kikuyu grasslands (Pennisetum clandestinum) compac-
tion is being caused by cattle stepping on top of poorly 
soil erosion rates while logging wet tropical forest in the 
Peninsula de Osa, at least partially, to the compaction of 
road surfaces. Tafur and Forsythe (1988) discovered that 
a slight increase in penetration resistance in sweet potato 
(Ipomoea batatas) plantations reduces the negative effect 
of Rhissomatus subcostatus (Coleoptera: Curculionidae) to 
the tubers; however, in the case of maize, disking the soils 
at field capacity reduced corn yield by 48% compared with 
disking the dry soil.

The main factors causing erosion under tropical humid 
conditions are when frequent rainfalls exceed the soil infil-
tration rate, hence increasing run-off, a problem aggravated 
by loss of soil cover. Also, catastrophic climatic events, in-
cluding tropical storms, hurricanes, floods, and drought, 
induce soil erosion, and geologic phenomena, including 
voleanic ash deposition and earthquakes, accelerate soil 
erosion. Overall, however, it is important to emphasize that 
many of these processes also form soils. The problem of 
erosion occurs when the natural factors interact with loss 
of vegetation cover, such as is generally the result of human 
activities on the land. In particular, the level of erosion is 
high in areas with greater road and human settlement den-
sity. This can be seen in a comparison of the Pacific Slope, 
which was settled first, with the Atlantic Slope. Even though
the Atlantic Slope gets more rain the Pacific Slope suffers from greater erosion impact.

Erosion in Costa Rica, according to the Tropical Science Center (TSC; 1991) is larger in areas planted with annual crops than in grasslands and relatively small when the land is planted with perennial crops. Even though estimated erosion values for the country steadily increased from 1973 to 1983, after this period soil losses have been stable, reaching an estimated value of 190,000 MT/year.

Conclusions

The variability of the soils of Costa Rica is almost as large as the number of different agroecosystems developed to match the varied ecological niches. Farmers and scholars (both national and international) have contributed to the development of more environmentally sound agricultural practices. Soil management errors of the past are lessons for the present. Therefore, new agricultural practices, including the use of soil inoculants (Rhizobium and Mycorrhizae), compost, minimum tillage, crop associations, and greenhouse operations, are now en vogue. It is expected that these approaches will lead to the conservation of soils, in terms of controlling both chemical contamination and physical erosion.

The considerations made here about soil organisms and land use changes on organic matter changes in the soil are pertinent in an environment where this type of knowledge is misused or little used. International studies on issues like soil carbon sequestration, recuperation of degraded lands, organic farming, use of imported inoculants, and recognition of bioindicators are examples of soil research that need less emphasis; on the contrary, soil research is needed to enhance nutrient use by crops, participatory approaches to involve more farmers into the generation of new knowledge, and identification of new agricultural possibilities with added value. Among the few alternatives to improve land (soil) use, ecotourism seems important. Additionally, an assessment of the carrying capacity of soils in Costa Rica’s main protected areas visited by ecotourists is also urgently needed.

This chapter shows that modern national and international soil research has contributed equally to elucidate soil-related issues and understand links among soils, ecosystems, and people in Costa Rica. The authors hope that this positive trend continues, not only in Costa Rica, but also in other countries on the American continent.

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Reran ¶


Reran ¶


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