SUSTAINABLE SOIL USE IN TROPICAL SOUTH AMERICA, WITH EMPHASIS ON BRAZIL

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1. Soil functions and sustainability

Soils provide plants with a medium in which roots can anchor themselves and support their canopies, and from which they can tap reserves of water and nutrients. To supply adequate space, water and nutrients, a good soil should be deep, permeable, porous, with good water and nutrient retention capacity and rich in a balanced amount of minerals and organic compounds. Most soils do not have these ideal characteristics. However, in their long period of evolution, plants adapted to almost any soil condition and covered most of the earth's surface, except for the harshest sites. Under these natural conditions, soil and plants maintain a continuous interaction where changes in the characteristics of soils and vegetation are mutually interdependent. Mineral nutrients cycle from soil to plants and back to the soil: absorbed by roots, incorporated into plant tissues, sometimes consumed by animals, then returned to the soil as litter which is decomposed by soil organisms. Soil losses by erosion are compensated by slow soil formation processes, so that a soil layer forms nearly everywhere, except steep slopes. These quasi-stable situations are considered sustainable.

Agriculture may alter this stability and increasingly so as more vegetation and soils are changed by human intervention. Questioning the need for this intervention is beyond the scope of this article since it ultimately refers to growth of the human population and its increasing demand for food and other plant products. These demands have led to an increasing use of marginal soils and greater inputs to raise agricultural output.

Agriculture disrupts nutrient cycles by exporting nutrients from agricultural fields to consumer sites. Thus, all agriculture eventually leads to nutrient depletion, an unsustainable situation, unless nutrients are replenished from outside. To replenish nutrients and to correct for original imbalances, fertilization and liming have been widely utilized. However, these inputs can create further imbalances in the availability of plant nutrients.

Agriculture requires the partial or total substitution of natural plant cover by one or more species, often with a vegetation structure different from the original. This substitution requires management. Elimination of the original cover requires cutting, removal or burning and weeding. This results in nutrient loss from the system. Establishment of the new plants requires seeding and frequently seed bed preparation by plough and harrow. Soil exposure to rain and wind under incomplete plant cover may result in erosion. To prevent water erosion, slopes may be altered by contour plowing, terraces and other conservation practices. This movement of soil and traffic of machines may result in the disruption of soil structure, compaction and surface crusting. Soil movement and disruption may also result in increased mineralization of soil organic matter to CO_2 with a double effect: further impoverishment of soil structure and release of nutrients which may be lost or absorbed and harvested. These processes are fastest under tropical and humid conditions.

Agriculture is frequently limited by water availability. Irrigation solves the problem but may create new ones if it increases soil salinity, alters the balance of nutrients and reduces soil permeability, or also if the water table rises too close to the surface, at lower landscape positions, creating waterlogged conditions, which most crop roots cannot tolerate.

Since it alters so many ecosystem characteristics, agriculture disrupts the original stability of any site where it is established. A new stabilization may be achieved and sound management practices may create stability at an appropriate production level. However, with continuous human intervention, there is always the risk of change beyond the limits of resilience and sustainability.

Although widely used, sustainability is not a clear and precise concept. It involves a concern for the environment and for its future condition. But it may be viewed from different perspectives and there is no set of acceptable measures to judge its value in any one place. Its use in agriculture is even more complicated because changes are inherent in the system. Technological advances may or may not solve present and future limitations and social and economic change may make present systems outdated. Sustainability can be viewed from this broad perspective, including not only maintenance of soil productivity but also maintenance of a clean environment, farm profitability, and fair distribution of social benefits. The following discussion of sustainability will be mostly restricted to agricultural productivity and pollution potential.

2. Tropical South America

The tropical area of South America from its northern point, close to 13^o N, to the tropic of Capricorn, covers about 12 million km^2 and has a large diversity of ecological conditions. Due to its latitude, temperatures are high and are seldom below freezing during the winter, except at high altitudes, like those of the Andean mountains. Rainfall ranges from abundant (>3000 mm $year^{-1}$) to scarce (<50 mm $year^{-1}$) and from well distributed throughout the year to seasonal, and highly erratic. Geologic formations date from old Paleozoic to recent quaternary and soils derived from these parent materials can be highly weathered or recent, deep to shallow, fertile to almost devoid of nutrients and heavy clayey to coarse sand. Vegetation ranges from humid tropical forests to sparse shrub desert.

Human occupation is the most recent of all continents, the first inhabitants having arrived sometime between 15 000 and 30 000 years ago. Before the arrival of Europeans, population was not very dense, except in a few places. Since the European colonization, population has grown steadily but with an irregular distribution, most of the people concentrating less than 100 km from the coasts. Part of the reason for this distribution was the colonial interest in producing export crops. This survived the formation of independent countries and still influences agricultural patterns.

The whole diversity of agricultural systems within the vast tropical South America area cannot be dealt with in the limited space of this text. Therefore, three broad environmental regions were selected: the Amazonian, the savanna and the semi-arid regions. Some other important regions will not be treated, mainly the Andean plateau and coastal zones. These two are the oldest large agricultural areas in the continent and, thus, are the most influenced by human intervention. The three selected regions still have large uncultivated portions. These regions are treated in a general way, barely considering their vast complexity but it should be remembered that each one could be further subdivided into several contrasting situations.

2.1. Amazonian region

The Amazon region comprises about 4 million km^2 in Brazil and another 3 million in Peru, Bolivia, Colombia, Venezuela, Surinam, Guyana, Ecuador and French Guyana. The climate in the region is characterized by high temperatures and high rainfall (>1500 mm yr^{-1}) throughout most of the year. It corresponds to the watershed of the Amazon river, a large plain without high altitudes except on its borders. Native vegetation is mostly upland tropical rainforest with several subtypes, usually related to soil quality. Seasonally flooded forests occupy a smaller portion and some areas do not support forests but lower and/or more open types of vegetation. Primary productivity and biodiversity are high, especially in the upland forest.

This vast region had a sparse native population and this population has grown little since European colonization (present densities are in the region of 1-2 inhabitants per km^2), except around a few more developed urban centers. Historically, settling occurred mostly on the margins of the many rivers of the region but, in the last few decades, it has also occurred in a few areas where roads and agricultural colonization projects have been established.

Most of the traditional inhabitants practice slash-and-burn subsistence agriculture (cassava, rice, beans, corn, banana, plantain) in small plots (<1 ha) that are cultivated for 2 to 3 years and left to fallow for long periods (decades), allowing the native forest to regrow to its original size and restoring soil fertility levels. A large portion of these plots are in seasonally flooded areas. Gathering of native vegetation products is an important part of their economy and some of these products, such as rubber, nuts, and fruits provide their main cash income. Selected perennial species are also planted within and around these plots which may be visited long after crops have been abandoned and forest regrowth is progressing. The total area of native forest that has been modified by this practice is an open question.

Past attempts to establish large improved agriculture areas have mostly failed, as have attempts to establish rubber or commercial timber production based on a few highly productive species. Recent development, mainly driven by opening of new roads, usually starts with timber extraction, followed by slash and burn agriculture and then pasture establishment for beef cattle production. Farmers with small plots (<50 ha) may not move to cattle production and their subsistence agriculture cycle could have fallow periods shorter than necessary to allow recovery of soil fertility, except if they occupy areas with good soils, a small proportion of the total Amazonian region. Presently, estimates of the total area that has been cleared for agriculture varies from 10 to 20%. Factors that limit agricultural development are social, economic and environmental, interacting in a vicious cycle. Sparse population, hence lack of local markets, and lack of transportation infrastructure to allow interchange of inputs and products, have limited agricultural activities to low input systems within narrow strips along rivers. Low soil fertility and high losses of nutrients from open areas, rapid re-invasion by native plants, and high rainfall and temperature, which lead to high soil organic matter decomposition and fast deterioration of agricultural products, have resulted in short cultivation periods and low productivities of common crops. Annual crops are cultivated for only a few years and pastures degrade in less than a decade. Fertilizers are not used due to their relatively high prices and local unavailability, a result of high transportation costs.

About 75% of the region contains deep, acid and infertile oxisols and ultisols, a result of high weathering due to continuous leaching at high temperatures. Smaller proportions are occupied by even less fertile spodosols, which support a low forest vegetation, and by nutrient rich alfisols and mollisols. Amazonian oxisols and ultisols are poor in nitrogen (N is limiting in 90% of the region), phosphorous (P, 90%), potassium (K, 80%), calcium (Ca, 60%), magnesium (Mg, 60%) and sulfur (S, 60%), and may be also limited by micro-nutrients (Zn, Cu, B, Mo), although data are scarce. Native vegetation maintains an almost closed nutrient cycle, where most of the nutrients are held in the standing biomass of trees and in the litter layer on top of the soil which is mingled with roots absorbing nutrients as soon as they are released from decaying matter, before they are leached to the soil. Clearing the forest for implementing agricultural crops leads to the export of nutrients in timber as well as in nutrient losses due to burning (N), leaching, and the removal of ashes in run off (other nutrients). After forest clearing, any remaining organic debris and roots decompose very rapidly, further releasing nutrients which may not be retained by the soil or the new vegetation. Besides the decrease in nutrient stock, availability is reduced as mineral and organic matter complexes are destroyed and nutrients (mainly P) form more stable complexes with iron and aluminum oxides and hydroxides. The decrease in soil organic matter also results in the deterioration of soil physical conditions, making the soil more liable to crusting, compaction and erosion, and reducing nutrient and water retention capacity.

Sustainable agriculture in the region could be attained by providing external sources of nutrients and by maintaining an adequate level of soil organic matter. A few natural external sources contribute nutrients. They include:

- Fixation of atmospheric N by symbiosis of microorganisms and plants, mainly legumes. At least 1300 legume species grow in the region and more than 300 of them are known to fix N_2;
- Airborne nutrients in dust and rainfall, which make small contributions of several nutrients, mainly S, Mg and K;
- Upstream sediments deposited in flooded areas, which usually have a higher fertility than upland soils; and
- Recovery of deep soil nutrients by extended root systems, which provides a limited supply.

External, anthropogenic nutrient sources (fertilizers, lime and manure from domestic livestock) are expensive and are not economically viable in most of the agricultural area. Their use may eventually become feasible if fertilizer prices are reduced, which can only be expected by lowering of transportation costs, and/or if prices of agricultural products increase. Prices of agricultural products have historically decreased but they could rise if demand increases and supply becomes limited by available agricultural land. Fertilizer and/or lime application becomes inefficient in most Amazonian soils after soil organic matter drops to very low levels because, once the buffer provided by organic matter is lost, it is hard to achieve a balanced nutrient supply. Unbalanced nutrient availability may be detrimental to crop production. Therefore management efforts should aim at the maintenance or increase of soil organic matter levels.

Protecting the soil and maintaining soil organic matter is difficult with annual crops, so land use practices involving perennial species, mainly trees, have been widely recommended. These perennials may be planted as single stands of native or introduced species, whose products may vary from timber to fruits, or, preferably, as a combination of species, since diversity may increase resilience. This combination may include annual plant species in agroforestry systems. In these systems, green manure crops, usually legumes, have also been recommended in order to offset N losses but they are not easily adopted because most offer no valuable product. In addition, the management of the native vegetation through selective tree cutting to allow both timber extraction and the gathering of other forest products, combined or not with an increase in the density of desired species, have been recommended as a sustainable option for soil use in the region.

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