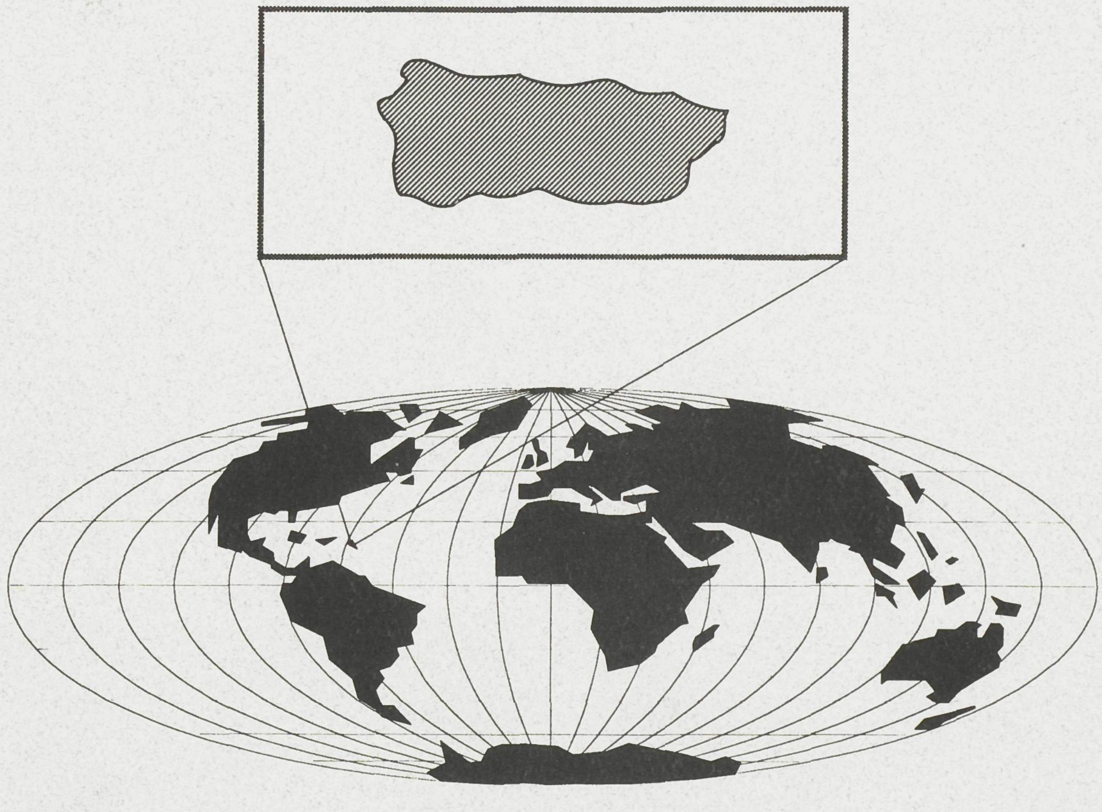
Organic Carbon Sequestration in the Soils of Puerto Rico

A Case Study of a Tropical Environment



UNIVERSITY OF PUERTO RICO
MAYAGUEZ CAMPUS
Department of Agronomy and Soils

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
World Soil Resources

Organic Carbon Sequestration in the Soils of Puerto Rico

A Case Study of a Tropical Environment

G. Acevedo, F.H. Beinroth, B.C. Dubee, A.M. Esnard,

P.J. Hernández, L.H. Liegel, M.A. Lugo-López

F.H. Beinroth
Editor

A Joint Publication of the

UNIVERSITY OF PUERTO RICO
MAYAGÜEZ CAMPUS
Department of Agronomy and Soils

and the

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
World Soil Resources

FEBRUARY 1992

For additional copies, write to:

Dr. F.H. Beinroth
Dept. of Agronomy and Soils
University of Puerto Rico
P.O. Box 5000
Mayagüez, PR 00681-5000
USA

Dr. Hari Eswaran
World Soil Resources
USDA Soil Conservation Service
P.O. Box 2890
Washington, DC 20013
USA

Design and Typography by
Dayton Publishing Services
Mayagüez, Puerto Rico

Printed in the United States of America
OMNIPRESS, Madison, Wisconsin

Organic Carbon Sequestration in the Soils of Puerto Rico

A Case Study of a Tropical Environment

CONTRIBUTORS

Gilberto Acevedo	Staff Soil Scientist USDA Soil Conservation Service San Juan, Puerto Rico
Friedrich H. Beinroth	Professor of Soil Science University of Puerto Rico Mayagüez, Puerto Rico
Bruce C. Dubee	Soil Scientist USDA Soil Conservation Service San Juan, Puerto Rico
Ann-Margaret Esnard	Graduate Research Assistant University of Puerto Rico Mayagüez, Puerto Rico
Pedro J. Hernández	Graduate Research Assistant University of Puerto Rico Mayagüez, Puerto Rico
Leon H. Liegel	Research Forester USDA Forest Service Corvallis, Oregon
Miguel A. Lugo-López	Professor Emeritus University of Puerto Rico Mayagüez, Puerto Rico

EDITOR

FRIEDRICH H. BEINROTH

MANAGING EDITOR

DAVID DAYTON

Organic Carbon Sequestration in the Soils of Puerto Rico

A Case Study of a Tropical Environment

Contents

Introduction

Friedrich H. Beinroth

The United Nations Conference on the Environment and Development (UNCED) to be held in Rio de Janeiro this June will, in all likelihood, mark the beginning of a new phase in the global environmental debate. In this phase, the emphasis will be on solutions rather than problems, on actions rather than rhetoric. There is reason to hope that the 160 nations to convene at the UNCED will agree on a comprehensive program for the 21st century, Agenda 21, to achieve sustainable development. High on this agenda is the most global of problems: climate change caused by the "greenhouse effect."

As the issue of global warming moves from academia into the political arena, world leaders can be expected to call upon the scientific community to develop paradigms that effectively and systematically address the challenges and turn the international aspirations into achievements.

Carbon dioxide is considered to be responsible for about half of the potential greenhouse warming, with methane, nitrous oxides, and chlorofluorocarbons making up the other half. Agricultural practices and land use changes, including the conversion of forests to agricultural land, contribute about one-third to the annual increase in carbon dioxide because the plant and soil carbon oxidized through these practices exceeds the amount being fixed by photosynthesis.

The carbon contained in the soils of the world constitutes the largest non-fossil terrestrial reservoir of carbon—nearly three times as much as the carbon in vegetation. Since a large part of this pool is potentially available to the atmosphere through human activities, it is obviously an intriguing and promising endeavor to explore the potential of carbon sequestration in soils for mitigating global climate change. One could argue, for example, that an increase of 10 percent in the carbon content of the soils of the world could conceivably withdraw 20 percent of the carbon in the atmosphere. What effect this would have on the global climate is speculative, however, as any assumption would be clouded by a great deal of uncertainty due to the scarcity of reliable data and models. Although the potential exists for significant changes in temperature at the surface of the globe, there is much doubt about the magnitude and even some ambivalence as to whether the changes will be positive or negative. Not surprisingly, this data dilemma was a recurrent theme at a recent workshop on carbon sequestration in soils held in Corvallis, Oregon, under the auspices of the U.S. Environmental Protection Agency.

It is in the context of this perspective on the global warming question that the present study was undertaken, funded by a grant from the USDA Soil Conservation Service. The objectives were to document and evaluate the soil carbon status in a tropical environment and to identify subject matter areas for future research.

The study's findings are presented here in four major sections. The first is an overview of carbon sequestration in soils of Latin America. It is followed by a literature review on soil organic matter research in Puerto Rico. The third section covers the organic carbon content of the soils of Puerto Rico and includes a discussion of the data and the methodology. The concluding section presents a set of recommendations containing the research imperatives that became apparent during the course of the study.

As pointed out in the report, there are indications of a number of probable cause and effect relationships that control carbon accumulation in tropical soils. Regrettably, they could not be explored under the terms and conditions of this grant, but it is hoped that they can be probed under a follow-up grant.

In view of the scale and urgency of the environmental challenges that must be faced as the planet's population doubles, massive research efforts need to be initiated now. Addressing the topics identified in this report would be a good beginning.

An Overview of Carbon Sequestration in Soils of Latin America

Leon H. Liegel

Abstract

Some scientists believe that deforestation is a major contributor to global climate warming because carbon dioxide and other gases are released to the atmosphere from biomass burning. Others provide evidence that existing soils, and forests growing on them, act as sinks rather than sources of atmospheric carbon. Latin America contains the largest reserve (46 percent) of remaining tropical forests and claims productivity figures for exotic forest species of >100 $m^3\ ha^{-1}\ yr^{-1}$. An evaluation of the carbon sequestration potential of Latin America's soils and forests, therefore, is a timely subject.

If soil carbon in Latin America's tropical forests is proportional to actual tropical forest land area, then at least 155 Pg of soil carbon are stored there. Estimates of carbon densities in above-ground vegetation range from 53 to over 200 Mg ha^{-1}, depending on the data sources and methodologies used. Studies on soil carbon accumulation rates are few. Observed annual rates of 30 to 50 g m^{-2} over a 40-year period in Puerto Rico compare to annual rates of 30 to 100 g m^{-2} over 20- to 80-year periods in temperate areas.

Carbon accumulation and loss are greatly influenced by management practice and inherent soil properties. The best management practices to increase soil carbon are those which lower soil temperature, maintain high base status, and retain soil aggregates and soil structure. When possible, incorporating lime and fertilizers on clay soils and soils having oxides of aluminum and iron also aids carbon accumulation processes. If growing forest biomass is viewed as a significant way to sequester carbon, then moist and wet, and even dry, subtropical/tropical areas offer greater potential than temperate regions because their growth rates are orders of magnitude higher. Maximum biomass sequestration rates have been observed using agroforestry practices.

Although Puerto Rico was more than 90 percent deforested by the late 1800's, surface horizons in many local soils still have up to six percent organic matter content and subsurface horizons frequently have $\geq$2 percent organic matter. Because of mass population movement to cities and the abandonment of much agricultural land

since the 1960's, more than one-third of Puerto Rico now has young to old secondary forest. The diverse mix of agricultural, forest, and highly urbanized landscapes offers unique research opportunities to study soil carbon pools and accumulation rates in several ecosystems. In agricultural ecosystems, potential studies include those aimed at: correlating total soil carbon and accumulation rates with clay content and soil mineralogy; relating observed total carbon pools to past/present cropping systems and land use changes; characterizing resiliency of Puerto Rican soils with those of other upland and lowland subtropical/tropical sites based on comparison of organic carbon to depths >1 meter; and determining which kinds of soils are most suitable for melanin production and carbon/nitrogen storage by fungi and other rhizosphere organisms. Possible forest ecosystem research would include studies to: correlate existing secondary forest inventory growth information with new root and total soil carbon data; make periodic carbon accumulation comparisons between forests and nearby pasture, crop, and urban lands; and evaluate the role of litter mulches from native and planted forests in promoting carbon retention in soil micro- and macroaggregates.

Introduction

Over a decade ago, deforestation in tropical areas was proclaimed the harbinger of accelerated erosion, diminished biodiversity, and reduced soil fertility (Myers 1980). More recently, deforestation is viewed as a major contributor to global climate warming because carbon dioxide and other greenhouse gases are released to the atmosphere from biomass burning (Houghton and Woodwell 1989, Crutzen and Andreae 1990). Additional and substantial amounts of carbon are released to the atmosphere when upper soil layers are disturbed for either agricultural or forestry purposes (Goreau and de Mello 1988). Parallel beliefs, however, are that temperate ecosystems must be carbon sinks to balance the world's carbon budget (Tans et al. 1990) and that tropical and temperate forests store significant amounts of carbon in above- and below-ground biomass (Marland 1988, Sedjo 1989). A logical extension of these beliefs is that both soils and forests can be aggressively managed to act as sinks rather than sources of atmospheric carbon (Johnson and Kern 1991, Winjum and Schroeder 1991).

A real problem in resolving the source or sink dilemma (Woodwell et al. 1978, Lugo and Brown 1980, Duxbury et al. 1989) is finding studies that assess above- and below-ground carbon stores within agricultural and forestry contexts. All too frequently in the past, agronomists and soil scientists limited their work to fertility characterization of mineral soils (Brady 1974, Tisdale and Nelson 1975), whereas foresters and ecologists primarily sampled aboveground productivity and chemical status of various vegetative components (Odum and Pigeon 1970, Leaf 1973, Edmonds 1982). Studies have often omitted bulk density measurements, thus precluding the calculation of soil organic carbon per unit area (Schlesinger 1984, Lugo and Brown 1991).

In this paper we review the potential of soils and forests in Latin America[1] to sequester carbon, using published literature from forestry and agricultural disciplines. The term *forests* includes primary and secondary natural forest vegetation, trees established via afforestation or reforestation practices, and trees planted in various agroforestry systems. Latin America contains the largest reserve (46 percent) of remaining tropical forests (Lanly 1989) and claims some of the largest productivity figures (70 to 100 m^3 ha^{-1} yr^{-1}) for commercial forest plantations in the world (Garcia Brandao 1984). In light of international concern about the urgency of mitigating the global warming phenomenon (Scharpenseel et al. 1990, U.S. Congress 1991), an evaluation of the carbon sequestration potential of soils and forests in Latin America seems timely.

The World Soil Resources Office of the USDA Soil Conservation Service also has a special interest in the carbon sequestration potential of major ecosystems, including tropical ones in Puerto Rico. When possible, then, specific examples are given for Puerto Rico, where former colonial politics and agricultural policies caused some 90 percent of the island to be deforested by the late 1800's. From the 1960's to the present, agricultural activities have diminished as rural people migrated to cities for better jobs and modern oceanic and air transportation allowed importation of most foodstuffs from the United States. As a result, over one-third of the island is now reforested (Birdsey and Weaver 1983). Thus, the very active mix of steep-hillside small farms, costal large-scale agroindustries, and expanding secondary forests have created a unique outdoor laboratory. In it, one can study the effects of land use changes on soil biological, chemical, and physical properties,

[1] Latin America, throughout this paper, comprises all countries of Central and South America, from the United States-Mexico border south to Tierra del Fuego, plus all islands in the Caribbean. Linking islands of the Caribbean with Central American nations is possible because their joint history and social change patterns reflect those of small nations influenced by powerful external interests (Adelman and Reading 1984).

including organic carbon loss or accumulation in agricultural, forest, and urban landscapes.

The subject matter of this paper is arranged in four major sections. In the first, existing carbon storage pools and accumulation rates in soils and forests are outlined, and in the second, rates of soil carbon loss are discussed. Land management practices that foster soil carbon sequestration are enumerated in the third section, and in the fourth and final one, knowns and unknowns about sequestering carbon in forest biomass via planting and afforestation operations are summarized. The paper closes with some general conclusions.

Carbon Pools and Accumulation Rates

Soils

The most recent estimate of total soil organic carbon, some 1,300 to 1,500 Pg (Schlesinger 1984, Hall 1989, Post et al. 1990) is intermediate between lower (700 Pg: Bolin 1970) and higher (3,000 Pg: Bohn 1976) calculated values. Using this estimate, soils store about three times more carbon than the world's vegetation and about two times more than the atmosphere. Assuming that soil carbon in tropical forests is proportional to actual forest land area (46 percent: Lanly 1989, Grainger 1990), then at least 155 Pg of soil carbon are stored in Latin America's tropical forests (Post et al. 1982). This amount is comparable to soil carbon stored in the world's wet and moist boreal forests (181.9 Pg) and cultivated lands (167.5 Pg).

A lingering myth about tropical soils is that organic matter content is quite low because of constant warm temperatures and abundant rainfall. Although many tropical soils show no dark organic color as do temperate soils, organic matter content can be high. For example, across many tropical countries and several orders of mineral soils, Sanchez (1976) reported organic matter values that ranged from less than 1.8 to 22.8 percent; comparative values for temperate forests and prairies were <3.5 and 5.3 percent, respectively. In Puerto Rico, Smith et al. (1951) found organic matter values from 1 to 6 percent in upper soil horizons and values between 1 and 2 percent frequently in lower horizons. Very high values, >10 percent, are associated with Andisols, derived from volcanic ash materials having high amounts of allophane. Probable mechanisms favoring high organic matter in Andisols are physical complexing between allophane and organic matter plus lessened microbial growth and reduced mineralization because of phosphorus deficiencies, cooler soil temperatures, and higher soil moisture (Sanchez 1976, Tan 1984).

Forests

According to Post et al. (1990), about 574 Pg of carbon are stored in above-ground vegetation of the world's terrestrial ecosystems. Based on Food and Agriculture forest stand volumes, Brown and Lugo (1984) estimated that 102 Pg of carbon are stored in closed and open tropical forests, representing an average weighted carbon density of 53 Mg ha^{-1} for several forest types. This amount was 43 percent of another estimate, 124 Mg ha^{-1}, calculated by the same authors (1982), but based on published organic matter storage data for six life zones; their 1984 estimate was 28 percent of that suggested by Whittaker and Likens (1973) for two forest types. In the Tropical Americas, above-ground biomass densities ranged from a high of 155.1 Mg ha^{-1} in undisturbed broad-leaf forest to a low of 33.3 Mg ha^{-1} in unproductive open forest. Corresponding figures for Tropical Africa and Asia were respectively 237.7 and 196.3 Mg ha^{-1} for undisturbed broad-leaf forest and 20.6 and 26.3 Mg ha^{-1} for unproductive open forest lands. Comparative above- plus below-ground biomass figures for temperate forests, as modeled by Cooper (1983), were 200 to >300 Mg ha^{-1}. Clouding these estimates, however, are concerns about field errors in accurately determining total biomass (Hase et al. 1985).

Soil Carbon Accumulation Rates

An important issue is to determine whether or not soil carbon accumulation rates are sufficient to delay or prevent global warming. The rate of carbon accumulation in soils is a function of many factors, but the balance between primary production (i.e., photosynthetic carbon fixation) and decomposition is the key. If primary production inputs to the soil exceed decomposition, carbon accumulates. If primary production equals decomposition, no net gain or loss of soil carbon occurs. If decomposition exceeds primary production, soil carbon is lost from ecosystems.

Soils developing in newly formed parent material, such as from volcanic lava and debris mudslides, lack the biology, physical structure, and chemistry needed to fuel significant primary production. As the soil becomes more organized, colonized, and structured, productivity accelerates in a buildup phase, as do accumulation rates (Jeny 1984, Figure 1). Accumulation rates eventually slow until, under long-term conditions of similar vegetation and climate, a steady state carbon carrying capacity is reached. Soils with the greatest potential carbon accumulation rates are most likely those that are somewhat carbon deficient but complete with the requisites (nutrients, biology, and structure) for primary production. Because the global extent of such soils seems great (Oldeman et al. 1990, WRI 1990), the potential exists to sequester significant amounts of atmospheric carbon in the short term (50-250 years).

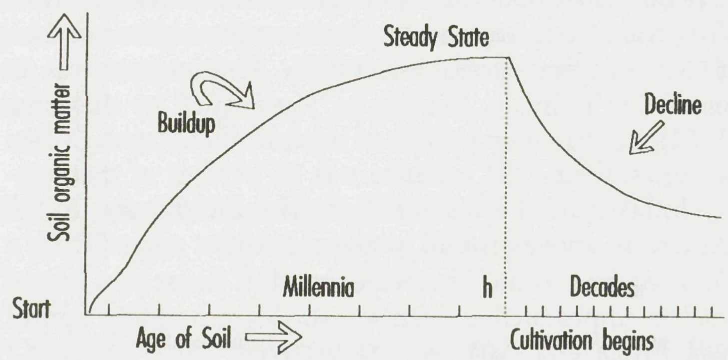


Figure 1. A generalized concept of soil organic matter build-up over millennia and subsequent destruction in decades under disturbance by cultivation (Jeny 1984).

For newly formed land surfaces in natural upland ecosystems, long-term carbon storage ranged from 0.2 to >10 g m^{-2} yr^{-1}, respectively, from polar deserts to forests (Schlesinger 1990). Other rates of long-term (>25 years) soil carbon accumulation range from about 26 to 100 g m^{-2} yr^{-1} in forest systems and from 21 to over 200 g m^{-2} yr^{-1} in agricultural systems (see Table 1, next page). Even in southeastern Alaska, Alexander et al. (1989) reported soil carbon accumulation rates for forested soils that ranged from 29 to 113 g m^{-2} yr^{-1}. And on soils that were carbon-depleted by long-term continuous agriculture, carbon accumulation rates were 20 to 50 g m^{-2} yr^{-1}after these lands were abandoned and naturally revegetated by mixed deciduous forest (Jenkinson 1991). The longest measurement time period for carbon accumulation in either system was less than a century.

In boreal ecosystems, peat carbon in coastal wet sites of Alaska is accumulating at rates of 6.3 to 22.7 g m^{-2} yr^{-1} (Barnett and Schell 1991). Only about 20 percent of the world's tropical peatlands and wetlands occur in Latin America (Andriesse 1985). Such lands, however, possibly accumulate peat and sequester carbon at rates three times faster than in temperate peatlands (Anderson 1964).

TABLE 1. Examples of soil carbon accumulation rates in fields and forests under various management practices.

Ecosystem	Practice	Site	C-rate $g\ m^{-2}\ yr^{-1}$	Time yr	Ref. #
Agriculture	Manuring	England	52	80	1
"	"	"	81	60	1
"	Low intensity	Georgia	61	40	2
"	Manuring	India	240	10	3
"	Min. tillage	Oregon	21	25	4
"	Abandonment	Puerto Rico	30-50	40	5
Woodland	Old field	England	26	80	6
"	"	"	53	80	6
Forest	N-fixation	Washington	68	26	7
"	Succession	Oregon	97	31	8
"	"	North Carolina	28	38	9

[1]Jenkinson and Rayner (1977)
[2]Jones et al. (1966)
[3]Shinde and Ghosh (1971)
[4]Rasmussen and Smiley (1989)
[5]Lugo et al. (1986)
[6]Jenkinson (1971, 1991)
[7]Tarrant and Miller (1963)
[8]Binkley et al. (1982)
[9]Boring and Swank (1984)

Conservation of these lands is managerially important because sequestered carbon will be lost if they are drained for agriculture and urban development.

In Africa after only two years, organic carbon increases ranged from 17 (1.30 to 1.53) to 30 (1.30 to 1.70) percent; bulk densities decreased 5 (from 1.42 to 1.35 g cm^{-3}) to 20 (from 1.42 to 1.1 g cm^{-3}) percent, depending on species of cover crop established (Lal et al. 1979). In Costa Rica over a ten-year period, using shade trees with cacao increased soil organic material by 42 or 16 Mg ha^{-1}, respectively, for legume and non-legume shade tree species (Beer et al. 1991).

In Puerto Rico, Weaver et al. (1987) found bulk densities and soil organic matter contents in the top 23 cm to be significantly higher under moist forest (1.02 g cm^{-3} and 8.99 kg m^{-2}) than wet forest (0.95 g cm^{-3} and 7.30 kg m^{-2}) life zones; significant differences existed for organic matter content under various timber classes, soil groups, and forest types. Lugo et al. (1986) found that organic carbon accumulation was higher in dry forest than in wet and moist forest life zones. After 40 years, reduced land use intensity increased soil carbon some 30 to 50 g m^{-2} yr^{-1}; soils still in active cultivation for pastures or crops had carbon/nitrogen ratios <12, values typical for stable soils. These data showed that despite past intensive land use, significant soil carbon had not been lost to the atmosphere as suggested by studies of tropical deforestation (Myers 1980, Fearnside 1985) and land clearing (Uhl and Guimaraes Vieira 1989). The overall conclusion was that intensively managed soils, particularly those under pasture and secondary forests, could well be carbon sinks rather than sources of carbon to the atmosphere.

Carbon Loss and Sequestration in Soils

One study covering long-term experiments from across the world estimated average soil carbon loss to be about 20 percent (Mann 1986). Soil carbon losses after cultivation in dry environments are estimated at 2 percent after 20 years and from 35 to 40 percent after 60 years (Rasmussen and Smiley 1989). In Peru, Alegre and Cassel (1986) observed a 21 percent loss in organic carbon in less than two years. Models using northern European data predict that new equilibrium levels after cultivation may take 100 years (Van der Linden et al. 1987).

On a chronosequence in Puerto Rico, soil carbon at 50 cm depth for mature subtropical forest was approximately 119 Mg ha^{-1}. After 10 years of cultivation, soil carbon dropped to about 66 Mg ha^{-1}, a loss of roughly 45 percent. Some 50 years after abandoning agriculture, soil carbon under secondary forest was about 112 Mg ha^{-1}, roughly 94 percent that of mature forest; the past fertilization history of the abandoned site was not known. From their results, Lugo et al. (1986) concluded that soil carbon under continuous cultivation reaches a point where additional losses are not possible, regardless of life zone. This limit could be related to the source of carbon in inactive pools or microaggregates (Tiessen et al. 1984) that have very slow turnover rates. Smith et al. (1951) observed high organic matter contents in surface horizons of Puerto Rican soils, from 1 to 6 percent. These soils represented different textures, depths, clay mineral types, and nutrient status classes. Possible but unproven causal agents were the proportion of native legumes in local forests and abandoned pastures and the overall high clay content of the island's soils.

In Brazil, organic matter in soils converted to pasture reached an equilibrium level equal to that under former secondary forest in 6 years; however, soil carbon in land converted to sugar cane from forest vegetation still had not reached equilibrium after 50 years of cultivation (Cerri and Andreux 1990). Over a four-year period in Puerto Rico, Lugo-López et al. (1956) reported little difference in sugar cane yield or organic matter levels in an Oxisol on which sugar cane trash was burned on site or incorporated as mulch; but erosion losses on the steep cultivated slopes were ten times greater on the burned site. They observed that organic matter could be increased (from 2.26 to 2.81 percent) within 20 months after adding sugar cane waste to other clayey soils that did not have the open, porous fabric of Oxisols.

One possible explanation for high organic matter in tropical soils, despite higher ambient temperatures, greater decomposition, and higher respiration rates than in temperate areas, is sequestration of carbon within melanins. These are dark-colored polymers associated with cell walls or culture media of fungi, actinomycetes, and some bacteria (Linhares and Martin 1978). Some fungal melanins are relatively resistant to decomposition; the polymers share certain chemical properties of soil humic acids that are also resistant to degradation. Many melanin-producing organisms are associated with high stress areas such as deserts and alpine regions; this phenomenon may indicate that melanins protect organisms against ultraviolet light radiation and desiccation (Bell and Wheeler 1986). Nitrogen source can affect biodegradation of the melanins, and fixed nitrogen can be sequestered along with carbon in melanins. Thus, potential capture of both carbon and nitrogen in soils of tropical ecosystems, via melanin-producing organisms, could be great. Burning of crop and understory residues is thought to disrupt sequestration processes involving melanin production (Hill et al. 1990). Strategies must be developed that allow management of successional vegetation, crop and other organic residues, and forage production in ways that do not disturb melanin formation processes. In summary, management practices, life zone, and inherent soil biological, chemical, and physical properties affect organic carbon losses and potential carbon sequestration.

Management practices and soil characteristics that foster soil carbon sequestration were recently discussed at an international workshop (Johnson and Kern 1991). Overall, the three major management goals identified were to: maintain carbon stores, restore soil carbon, and enlarge the overall global pool of soil carbon. Using the workshop results plus information from Oades (1988), the following two sections give an overview of how suggested management practices and conditions affect Latin American agricultural and forestry situations.

Management Practices that Promote Soil Carbon Sequestration

Lowering Soil Temperatures

Because decomposition rates increase with increasing temperatures, practices that lower soil temperatures also slow decomposition. Lowering maximum soil temperatures are more critical than lowering mean soil temperatures (Buol et al. 1990). Leaving crop stubble on site rather than burning it, incorporating mulch, using minimum or no-tillage practices, and establishing grass or legume cover crops are ways to decrease soil temperatures (Lal et al. 1979). However, up to 50 percent of mulches in humid tropical areas can be lost within three months because of very high decomposition rates and termite activity (Lal et al. 1980). In natural forests, selective cutting of individual trees in small patches or strip clear-cuts (Hartshorn 1989) lowers soil temperatures; in plantations and natural forests, leaving residues behind after logging rather than burning them has the same effect. Such practices are possible for either small-scale, slash-and-burn (Sanchez 1976), or large-scale mechanized agricultural operations (Cochrane et al. 1985).

Clay Texture

Fine clay and high silt plus clay content soils retain more stable organic matter than do sandy soils (Tiessen et al. 1984, Parton et al. 1988, Vitorello et al. 1989), primarily because of greater surface area for binding organic matter to individual soil particles. As an inherent soil property, texture is not changed by management. However, by knowing that organic matter is held best by clay soils, land owners and managers can use practices such as mulching, minimum tillage, and patch or small strip clear-cuts (Hartshorn 1989, 1990) to increase organic matter in clay soils on their lands, even on steep slopes in humid tropical areas (Vicente-Chandler et al. 1966). Clay-textured families exist for most soil orders found in the tropics (Buol et al. 1980). Thus a great potential exists for maintaining and increasing organic matter in clay soils within Latin America. Some clay soils retain more moisture and therefore favorably influence the growth of various crop and tree species during dry periods (Magalhaes et al. 1986/87a, 1986/87b); well-structured and aerated Oxisols with high amounts of aluminum and iron oxides are an exception.

High Base Status

Calcium additions to soil help slow organic matter decomposition and improve soil structure (Sanchez 1976, Oades 1988). The probable mechanism is calcium acting as a "bridge" between organic matter and soil particles to form aggregates that are biologically, chemically, and physically stable. Predominant soil orders in the humid tropics, Oxisols and Ultisols (Pritchett and Fisher 1987), generally have low base status and low pH. Because cation exchange capacity is low, relatively small amounts of lime are needed to replace aluminum with calcium ions. Thus, liming and fertilizing acid soils in Latin America helps maintain soil fertility by enhancing base saturation. When forest fallows are long enough, cyclic low-input shifting cultivation adds bases to the soil from burned woody debris. Commercial fertilization of forest plantings does not seem economically feasible because limited financial resources for nutrient amendments are dedicated to producing food crops for increasing human populations. Using acid-tolerant, deep-rooting forest species allows recycling of calcium and other nutrients into surface horizons from lower soil depths.

Soil Aggregates

Formation of soil aggregates allows the binding of organic matter with soil particles. In cultivated soils, organic carbon within macroaggregates is generally mineralized more easily than carbon in microaggregates; larger aggregates are formed from transient and temporary cementing agents (Elliott 1986). Practices that minimize soil disturbance and that use deep-rooting plants or trees and incorporate organic matter into the soil (mulching and minimum tillage) increase cementing agents, thus promoting the formation of macroaggregates and encouraging carbon sequestration.

Traditional slash-and-burn agriculture, using hand tools, will not change soil physical properties (Nortcliff et al. 1988) whereas mechanized land clearing can destroy soil aggregates (Alegre and Cassel 1986). One way to foster good natural aggregation processes on forest lands is to limit deforestation; another is to intensify agricultural operations on smaller amounts of land, thereby reducing the need to clear additional forests (Nicholaides et al. 1985).

Variable Charge Clay Soils

Oxides of aluminum and iron also help "bridge" soil particles together with organic matter, as does calcium (Sanchez 1976). This inherent phenomenon exists for Ultisol and Oxisol soil orders and is not changeable by management practices. However, increasing soil fertility by liming and fertilizing allows incorporation of greater amounts of organic matter into soils where it is trapped between clays held together by oxide coatings (Coleman et al. 1989). Encouraging this process is more common in agricultural than in forestry operations where operational fertilization is not widely practiced.

Carbon Sequestration in Forest Ecosystems

Forest Growth Rates

Large-scale reforestation and/or afforestation projects are now viewed as managerially acceptable options to capture atmospheric carbon in forest biomass (Marland 1988, Houghton and Woodwell 1989, Sedjo 1989). For example, Harmon et al. (1990) calculated that harvesting old growth Pacific Coast Douglas-fir and hemlock (*Pseudotsuga* and *Tsuga*) forests since 1890, from only 0.017 percent of the world's land area, accounts for 2 percent of the biogenic carbon input to the atmosphere caused by land use change since 1890. Delcourt and Harris (1980) calculated that the southeastern United States became a net sink for carbon in the three decades prior to their article. Much of this increase was primarily in biomass and not in soil carbon stores (Schiffman and Johnson 1989).

Using published mean annual increments of stemwood biomass for individual countries and species is one way to begin assessing the suitability of forest species for carbon sequestration. Marland (1988) presented such data for the United States. Including all species and regions, the combined net growth was 3.2 m^3 ha^{-1} yr^{-1} in 1977. Table 2 shows comparative figures for other countries.

TABLE 2. Commercial forest growth in selected countries.[1]

Country/Region	Net Annual Growth (m^3 ha^{-1} yr^{-1})
Canada	1.7
China	1.5
Europe	3.3
Sweden	3-4
Tropical moist forest	6-15
United States (commercial)	3-5
United States (non-commercial)	0.7
USSR	1.1

[1]Adapted from Marland (1988)

Lugo et al. (1990) prepared productivity figures for plantation species in several tropical countries. Within the Tropical Americas, the range was from 5.2 to 161 Mg ha^{-1} yr^{-1}, for plantings 1.3-years old to 16-years old. These values were contrasted with biomass accumulated for five species, 5.5-years-old, grown in Puerto Rico. Total above-ground biomass for these species ranged from 7.2 to 39.1 Mg ha^{-1} yr^{-1} for local seed sources of *Leucaena leucocephala* and *Casuarina equisetifolia,* respectively. In dry uplands of Mexico and Argentina, median carbon storage in biomass under reforestation ranged from 41 to 112 Mg ha^{-1} (see Table 3, next page). Using agroforestry practices in humid tropical uplands of Mexico, median potential storage of carbon increased to 144 Mg ha^{-1}. These levels are comparable to those in many other countries, except Australia and the United States where intensive forest management practices produce even higher potential carbon storage values (Dixon et al. 1991).

Stand Manipulation

Two ways to manipulate a forest stand for greater biomass accumulation without massive energy inputs are density control and timing of harvest. Per unit time, stands of different densities generally produce the same amount of biomass: denser stands spread

TABLE 3. Estimated potential carbon storage for different forest management practices for three countries in Latin America.[1]

Country	Ecoregion	Practice	Carbon storage[2] Mg ha^{-1}	
Argentina	Humid temperate lowlands	Reforestation	66	(46)[3]
		Afforestation	63	(4)
	Dry lowlands	Reforestation	58	(60)
		Afforestation	53	(9)
	Dry uplands	Reforestation	41	(5)
Brazil	Dry lowlands	Reforestation	71	(1)
		Afforestation	116	(3)
	Humid tropical lowlands	Reforestation	65	(56)
		Afforestation	128	(1)
		Natural Regeneration	157	(2)
		Agroforestry	41	(4)
Mexico	Dry lowlands	Reforestation	98	(1)
		Agroforestry	98	(1)
	Dry uplands	Reforestation	112	(1)
		Agroforestry	97	(1)
	Humid tropical lowlands	Reforestation	78	(1)
		Natural Regeneration	41	(1)
	Humid tropical uplands	Reforestation	101	(6)
		Silviculture	31	(7)
		Agroforestry	144	(2)

[1]Adapted from Dixon et al. (1991).
[2]Values represent median of sample size for n observations.
[3]Values in parentheses represent number of observations (n) for each practice.

this biomass across many stems whereas less dense stands concentrate the same biomass on fewer and generally more merchantable stems (Smith 1986). For example, Parrotta (1989) found that dense stands (40,000 trees per hectare) of *Albizzia lebbek* produced only 63 and 86 percent of above-ground biomass produced in plots with densities of 10,000 and 2,500 stems per hectare, respectively .

In Brazil, Schacht et al. (1988) found no significant difference in quantity of forage produced beneath crown densities cleared to 0, 25, and 55 percent of the control which had 95 percent canopy cover. Thus, where wood biomass is not the final management objective, less than total deforestation still increased forage biomass some seven to eight times. This finding should help reduce indiscriminate deforestation in areas with similar forage requirements. Also, combining forage and forest vegetation should produce greater soil organic carbon than does forest vegetation alone because soil carbon content is generally higher under grass than forest vegetation (Sanchez 1976, Lugo et al. 1986, Long et al. 1989).

Residue Management

If forest fallows are sufficiently long between subsequent clearings, organic matter levels can probably be maintained at 75 to 80 percent of the levels that existed under primary natural forest (Sanchez 1976). Long-term studies have shown significant decreases in organic matter content of the upper 5 centimeters of soil after burning debris in clearcuts in Oregon; yet increases were reported for the same soil depth in South Carolina over a 20-year burning study (Wells et al. 1979). Fuel type, burn duration and intensity, climate, and soil properties determine if organic carbon is lost after burning forest residues. Residue management options that reduce burn intensity or eliminate burning will increase residues that are converted to soil organic matter. Woody debris left on site lowers soil temperatures and encourages continued growth of rhizosphere organisms, important for soil decomposition and aggregation processes.

Healthy Soil Rhizosphere

Factors usually associated with organic matter accumulation and aggregate formation are wetting and drying of soil, organic matter additions, root decay, activity of soil microorganisms, and cultivation practices (Wilde 1958, Alexander 1977). Across Latin America, intensifying agricultural practices on less land and reducing deforestation will help to maintain healthy rhizosphere relationships in natural forests. Planting forests on degraded, understocked sites will restore beneficial soil rhizosphere relationships by reducing soil temperatures, adding organic matter, and increasing soil moisture in upper soil horizons.

Agroforestry

Although definitions differ (MacDicken and Vergara 1990), agroforestry in its simplest form is the integrated and sustainable use of trees, food crops, and animals on the same land parcel. Sometimes, the amount of carbon stored per unit area of land under agroforestry systems is greater than that under reforestation, afforestation, or silvicultural practices alone (Dixon et al. 1991). Generalizations about this trend are difficult because productivity for any agroforestry system ultimately depends on the timing and kinds of crops grown, forest species used, crop and tree density, and the mixture of final products obtained. Some management benefits of agroforestry over open row crops are less nutrient leaching and more available soil water (Imbach et al. 1989). Managed natural and enriched successional vegetation, as occurs in forest fallows, protected against losses of carbon and nitrogen from volcanic ash soils in Costa Rica and diminished losses of available cations such as calcium (Ewel et al. 1991). Differences in soil nutritional status of the vegetated plots in Costa Rica were attributed to root turnover and proliferation differences between short-lived annual and longer-lived perennial crops.

Conclusions

From the selected literature reviewed, it appears that intensive agricultural management systems, in moist temperate and tropical climates, have the greatest carbon accumulation rates in soils: approximately 80 to over 200 g m^{-2} yr^{-1} over periods of 10 to 80 years. Forest systems have been studied less than agricultural systems, particularly in the tropics. Comparative accumulation rates in forest ecosystems are from 30 to almost 100 g m^{-2} yr^{-1}.

Carbon losses are quite rapid after soils are disturbed by agriculture and forestry activities (Alegre et al. 1988), particularly in moist tropical climates where year-long warm temperatures maintain high rates of organic matter breakdown. From the limited data available, converting forests to managed pastures in Brazil and Puerto Rico causes soil organic matter to reach levels observed under older secondary forest, over periods of a decade to 50 years;

converting forest to other land uses such as sugar cane slows the equilibrium process, producing organic carbon levels that are lower than those under forests (Cerri and Andreux 1990). Generalizations are difficult to make because the cropping systems used, the texture and fertility of the soil, local topography, and yearly climate all influence carbon accumulation and loss rates.

New research findings are important when assessing carbon sequestration potential of forage management systems. First, evidence from Brazil suggests that forage can be produced in association with tree cover rather than in total absence of tree cover (Schacht et al. 1988). This means that complete deforestation is not needed to produce forage crops under certain kinds of local soil-forage-tree associations. Second, when reproductive parts are included, tropical grasses across four countries were found to produce some three to five times more carbon on an annual basis than had been previously assumed (Long et al. 1989). It is unclear what proportion of this extra productivity is converted to soil carbon; however, the sum result is that grassland ecosystems, already recognized as superior to forests in total below-ground carbon storage, may be even more productive than previously thought. This fact has tremendous potential impact upon how grasslands are managed, by themselves or in conjunction with trees grown for commercial wood production. Reassessment may be needed for other vegetative types, like palms (Balick and Anderson 1986/87), that also allocate large amounts of carbon, some 34 percent, to inflorescence and fruits.

Literature Cited

Adelman, A., and R. Reading (ed.). 1984. Confrontation in the Caribbean Basin. 1984. Center for Latin American Studies, University Center for International Studies, University of Pittsburgh, Pittsburgh.

Alegre, J.C., and D.K. Cassel. 1986. Effect of land-clearing methods and post-clearing management on aggregate stability and organic carbon content of a soil in the humid tropics. Soil Science 142:289-295.

Alegre, J.C., D.K. Cassel, and D.E. Bandy. 1988. Effect of land clearing method on chemical properties of an Ultisol in the Amazon. Soil Science Society of America Journal 52:1283-1288.

Alexander, E.B., E. Kissinger, R.H. Huecker, and P. Cullen. 1989. Soils of southeast Alaska as sinks for organic carbon fixed from atmospheric carbon-dioxide. p. 203-210. *In* E.B. Alexander (ed.) Proceedings of watershed '89: A conference on the stewardship of soil, air, and water resources. USDA Forest Service Region 10, Juneau, AK. Publication R10-MB-77.

Alexander, M. 1977. Introduction to soil microbiology. 2nd ed. John Wiley and Sons, New York.

Anderson, J.A.R. 1964. The structure and development of peat swamps of Sarawak and Brunei. Journal of Tropical Geography 18:7-16.

Andriesse, J.P. 1985. Nature and management of tropical peat soils. FAO Soils Bulletin No. 59. Food and Agricultural Organization of the United Nations, Rome.

Balick, M.J., and A.B. Anderson. 1986/87. Dry matter allocation in *Jessenia bataua* (Palmae). Acta Amazonica 16/17:135-140.

Barnett, B., and D.M. Schell. 1991. Peat carbon accumulation rates in arctic Alaska. p 12. *In* Abstracts for symposium on carbon cycling in boreal forest and sub-arctic ecosystems: biospheric responses and feedbacks to global climate change, 9-12 September 1991. Oregon State University and US Environmental Protection Agency, Corvallis, OR.

Beer, J., A. Bonnemann, W. Chavez, H.W. Fassbender, A.C. Imbach, and I. Martel. 1991 (in press). Modelling agroforestry systems of cacao (*Theobroma cacao*) with laurel (*Cordia alliodora*) or poro (Erythrina *poeppigiana*) in Costa Rica. V. Productivity indices, organic material models, and sustainabilty over ten years. Agroforestry Systems.

Bell, A.A., and M.H. Wheeler. 1986. Biosynthesis and functions of fungal melanins. Annual Review of Phytopathology 24:411-451.

Binkley, D., K. Cromack, Jr., and R.L. Fredriksen. 1982. Nitrogen accretion and availability in some snowbrush ecosystems. Forest Science 28:720-724.

Birdsey, R.A. and P.L. Weaver. 1983. Puerto Rico's timberland. Journal of Forestry 81:671-672, 699.

Bohn, H.L. 1976. Estimate of organic carbon in world soils. Soil Science Society America Journal 40:468-470.

Bolin, B. 1970. The carbon cycle. Scientific American 223:124-132.

Boring, L.R., and W.T. Swank. 1984. The role of black locust (Robinia *pseudoacacia*) in forest succession. Journal of Ecology 72:749-766.

Brady, N.C. 1974. The nature and properties of soils. 8th ed. Macmillan Publishing Co., Inc., New York.

Brown, S., and A.E. Lugo. 1982. The storage and production of organic matter in tropical forests and their role in the global carbon cycle. Biotropica 14:161-187.

Brown, S., and A.E. Lugo. 1984. Biomass of tropical forests: A new estimate based on forest volumes. Science 223:1290-1293.

Buol, S.W., F.D. Hole, and R.J. McCracken. 1980. Soil genesis and classification. 2nd ed. Iowa State University Press, Ames.

Buol, S., P.A. Sanchez, S.B. Weed, and J.M. Kimble. 1990. Predicted impact of climatic warming on soil properties and use. p. 71-82. *In* B.A. Kimble, N.J. Rosenberg, and L.H. Allen, Jr. (ed.) Impact of carbon dioxide, trace gases, and climatic change on global agriculture. American Society of Agronomy, Madison, WI. ASA Special Publication 53.

Cerri, C.C., and F. Andreux. 1990. Changes in organic carbon in Oxisols cultivated with sugar cane and pasture, based on ^{13}C natural abundance measurement. p. IV.98-103. *In* Transactions of 14th International Congress of Soil Science, Volume IV, August 1990, Kyoto, Japan.

Cochrane, T.T., L.G. Sanchez, L.G. de Azevedo, J.A. Porras, and C.L. Garver. 1985. Land in tropical America, Vol. 1. A guide to climate, landscapes, and soils for agronomists in Amazonia, the Andean Piedmont, Central Brazil, and Orinoco. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia, and Empresa Brasileira de Pesquisa Agropecuaria, Centro de Pesquisa Agropecuaria dos Cerrados (EMBRAPA-CPAC), Planaltina, D.F. Brazil.

Coleman, D.C., J.M. Oades, and G. Uehara (ed.). 1989. Dynamics of soil organic matter in tropical ecosystems. University of Hawaii Press, Honolulu.

Cooper, C.F. 1983. Carbon storage in managed forests. Canadian Journal of Forest Research 13:155-1366.

Crutzen, P.J., and M.O. Andreae. 1990. Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles. Science 250: 1669-1678.

Delcourt, H.R., and W.F. Harris. 1980. Carbon budget of the southeastern U.S. biota: Analysis of historical changes in trend from source to sink. Science 210:321-323.

Dixon, R.K., P.E. Schroeder, and J.K. Winjum. 1991. Personal communications. U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR.

Duxbury, J.M., M.S. Smith, J.W. Doran, C. Jordan, L. Szott, and E. Vance. 1989. Soil organic matter as a source and a sink of plant nutrients. p. 33-67. *In* D.C. Coleman, J.M. Oades, and G. Hehara (ed.) Dynamics of soil organic matter in tropical ecosystems. University of Hawaii Press, Honolulu.

Edmonds, R.L. (ed.). 1982. Analysis of coniferous forest ecosystems in the western United States. US/IBP Synthesis Series 14. Hutchinson Ross Publishing Company, Stroudsburg, PA.

Elliott, E.T. 1986. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Science Society of America Journal 50:627-633.

Ewel, J.J., M.J. Mazzarino, and C.W. Berish. 1991. Tropical soil fertility changes under monocultures and successional communities of different structure. Ecological Applications 13:289-302.

Fearnside, P.M. 1985. Brazil's Amazon forest and the global carbon problem. Interciencia 10:179-186.

Garcia Brandao, L. 1984. The new eucalypt forest. p. 3-15. *In* Proceedings of Marcus Wallenberg Symposia #1, 14 September 1984, Falun, Sweden.

Goreau, T.J., and W.Z. de Mello. 1988. Tropical deforestation: Some effects on atmospheric chemistry. Ambio 17:275-281.

Grainger, A. 1990. Modelling the impact of alternative afforestation strategies to reduce carbon dioxide emissions. p. 93-104. *In* Proceedings of the conference on tropical forestry response options to global climate change, 9-11 January 1990, Sao Paulo, Brazil. U.S. Environmental Protection Agency, Office of Policy Analysis, Washington, DC.

Hall, D.O. 1989. Carbon flows in the biosphere: Present and future. Journal of the Geological Society, London 146:175-181.

Harmon, M.E., W.K. Ferrell, and J.F. Franklin. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. Science 247:699-702.

Hartshorn, G.S. 1989. Application of gap theory to tropical forest management: natural regeneration on strip clearcuts in the Peruvian Amazon. Ecology 70:567-569.

Hartshorn, G.S. 1990. A new approach to sustainable development of tropical forests. Western Wildlands 16:8-11.

Hase, H., H. Foelster, and M. Lindheim. 1985. On the accuracy of estimating above-ground tree biomass in an evergreen forest near Manaus, Brazil. A simulation study. Biotropica 17:191-195.

Hill, N.M., D.G. Partriquin, and K. Sircom. 1990. Increased oxygen consumption at warmer temperatures favors aerobic nitrogen fixation in plant litters. Soil Biology and Biochemistry 22:321-325.

Houghton, R.A., and G.M. Woodwell. 1989. Global climatic change. Science 260:36-44.

Imbach, A.C., H.W. Fassbender, R. Borel, J. Beer, and A. Bonnemann. 1989. Modelling agroforestry systems of cacao (*Theobroma cacao*) with laurel (*Cordia alliodora*) and cacao with poro (*Erythrina poeppigiana*) in Costa Rica. IV. Water balances, nutrient inputs, and leaching. Agroforestry Systems 8:267-287.

Jenkinson, D.S. 1971. The accumulation of organic matter in soil left uncultivated. p. 113-137. *In* Rothamsted Experimental Station report for 1970, Part 2. Harpenden-Herts, England.

Jenkinson, D.S. 1991. The Rothamsted long-term experiments: Are they still of use? Agronomy Journal 83:2-10.

Jenkinson, D.S., and J.H. Rayner. 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Science 123:298-305.

Jeny, H. 1984. The making and unmaking of a fertile soil. p. 42-55. *In* W. Jackson, W. Berry, and B. Colman (ed.) Meeting the expectations of the land. North Point Press, San Francisco.

Johnson, M.G., and J.S. Kern. 1991. Sequestering carbon in soils: A workshop to explore the potential for mitigating global climate change. U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR. EPA/600/3-91-031.

Jones, L.S., O.E. Anderson, and S.V. Stacy. 1966. Some effects of sod-based rotations upon soil properties. Bulletin N.S. 166. Georgia Agricultural Experiment Station, Experiment, GA.

Lal, R., G.F. Wilson, and B.N. Okigbo. 1979. Changes in properties of an Alfisol produced by various crop covers. Soil Science 127:377-382.

Lal, R., D. De Vleeschauwer, and R.M. Nganje. 1980. Changes in properties of a newly cleared tropical Alfisol as affected by mulching. Soil Science Society of America Journal 44:827-833.

Lanly, J.P. 1989. The status of tropical forests. Paper given at USDA Forest Service, Southern Forest Experiment Station, Institute of Tropical Forestry, Golden Anniversary Symposium, 24-26 May 1989. San Juan, PR.

Leaf, A.L. 1973. Plant analysis as an aid in fertilizing forests. p. 427-454. *In* L.M. Walsh and J.D. Beaton (ed.) Soil testing and plant analysis. Soil Science Society of America, Inc., Madison, WI.

Linhares, L.F., and J.P. Martin. 1978. Decomposition in soil of the humic acid-type polymers (melanins) of *Eurotium echinulatum, Aspergillus glaucus* Sp. and other fungi. Soil Science Society of America Journal 42:738-743.

Long, S.P., E. Garcia Moya, S.K. Imbamba, A. Kamnalrut, M.T.F. Piedade, J.M.O. Scurlock, Y.K. Shen, and D.O. Hall. 1989. Primary productivity of natural grassland ecosystems of the tropics: A reappraisal. Plant and Soil 115:155-166.

Lugo, A.E., and S. Brown. 1980. Tropical forest ecosystems: sources or sinks of atmospheric carbon? Unasylva 32:8-13.

Lugo, A.E., and S. Brown. 1991. Management of tropical forest lands for maximum soil carbon storage. p. 75-77. *In* M.G. Johnson and J.S. Kern. Sequestering carbon in soils: A workshop to explore the potential for mitigating global climate change. U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR. EPA/600/3-91-031.

Lugo, A.E., M.J. Sanchez, and S. Brown. 1986. Land use and organic carbon content of some subtropical soils. Plant and Soil 96:185-196.

Lugo, A.E., D. Wang, and F.H. Bormann. 1990. A comparative analysis of biomass production in five tropical tree species. Forest Ecology and Management 31:153-166.

Lugo-López, M.A., E. Hernandez-Medina, and P. Landrau, Jr. 1956. Differential response of some tropical soils to additions of organic matter. Journal of Agriculture of the University of Puerto Rico, 40:70-77.

MacDicken, K.G., and N.T. Vergara (ed.) 1990. Agroforestry: Classification and management. John Wiley and Sons, New York.

Magalhaes, L.M.S., W.E.H. Blum, and N.P. Fernandes. 1986/87a. Caracteristicas edafico-nutricionais de plantios florestais na regiao de Manaus. 1. Crescimento de *Eucalyptus deglupta* Blume em solos de diferentes texturas. Acta Amazonica 16/17:509-522.

Magalhaes, L.M.S., W.E.H. Blum, and N.P. Fernandes. 1986/87b. Caracteristicas edafico-nutricionais de plantios florestais na regiao de Manaus. 2. Crescimento de *Carapa guianensis* Aubl. em solos de diferentes texturas. Acta Amazonica 16/17:523-534.

Mann, L.K. 1986. Changes in soil carbon storage after cultivation. Soil Science 142:279-288.

Marland, G. 1988. The prospect of solving the CO_2 problem through global reforestation. Report No. DOE/NBB-0082. U.S. Department of Energy, Office of Energy Research. Washington, DC.

Myers, N. 1980. Conversion of tropical moist forests. National Academy of Sciences, Washington, DC.

Nicholaides III, J.J., D.E. Bandy, P.A. Sanchez, J.R. Benites, J.H. Villachica, A.J. Coutu, and C.S. Valverde. 1985. Agricultural alternatives for the Amazon Basin. Bioscience 35:279-285.

Nortcliff, S., and A. Carlos D.C.P. Dias. 1988. The change in soil physical conditions resulting from forest clearance in the humid tropics. Journal of Biogeography 15:61-66.

Oades, J.M. 1988. The retention of organic matter in soils. Biogeochemistry 5:35-70.

Odum, H.T., and R.F. Pigeon. 1970. A tropical rain forest: A study of irradiation and ecology at El Verde, Puerto Rico. U.S. Atomic Energy Commission. National Technical Information Service. Springfield, VA.

Oldeman, L.R., R.T.A. Hakkeling, and W.G. Sombroek. 1990. World map of the status of human-induced soil degradation: an explanatory note. International Soil Reference and Information Center, Wageningen, The Netherlands.

Parrotta, J.A. 1989. The influence of management practices on the biogeochemical stability of tropical fuel-wood plantations. Tropical Ecology 30:1-12.

Parton, W.J., J.W.B. Stewart, and C.V. Cole. 1988. Dynamics of C, N, P, and S in grassland soils: A model. Biogeochemistry 5:109-131.

Post, W.M., W.R. Emanuel, P.J. Zinke, and A.G. Stangenberger. 1982. Soil carbon pools and world life zones. Nature 298:156-159.

Post, W.M., T.-H. Peng, W.R. Emanuel, A.W. King, V.H. Dale, and D.L. DeAngelis. 1990. The global carbon cycle. American Scientist 78:310-326.

Pritchett, W.L., and R.F. Fisher. 1987. Properties and management of forest soils. 2nd ed. John Wiley and Sons, New York.

Rasmussen, P.E., and R.W. Smiley. 1989. Long-term management effects on soil productivity and crop yield in semi-arid regions of eastern Oregon. Station Bulletin No. 675. USDA Agricultural Research Service, Columbia

Basin Agricultural Research Center, Pendleton, OR, and Agricultural Experiment Station, Oregon State University, Corvallis.

Sanchez, P.A. 1976. Properties and management of soils in the tropics. John Wiley and Sons, New York.

Scharpenseel, H.W., M. Schomaker, and A. Ayoub (ed.) 1990. Soils on a warmer earth. Developments in Soil Science 20. Elsevier Science Publishing Company, Inc., New York.

Schacht, W.H., J.N. Long, and J.C. Malechek. 1988. Above-ground production in cleared and thinned stands of semiarid tropical woodland, Brazil. Forest Ecology and Management 23:201-214.

Schiffman, P.M., and W.C. Johnson. 1989. Phytomass and detrital carbon storage during forest regrowth in the southeastern United States Piedmont. Canadian Journal of Forest Research 19:69-78.

Schlesinger, W.H. 1984. Soil organic matter: A source of atmospheric CO_2. p. 111-127. *In* G.M. Woodwell (ed.) The role of terrestrial vegetation in the global carbon cycle: Measurement by remote sensing. John Wiley and Sons, New York.

Schlesinger, W.H. 1990. Evidence from chronosequence studies for a low carbon-storage potential of soils. Nature 348:232-234.

Sedjo, R.A. 1989. Forests to offset the greenhouse effect. Journal of Forestry 87:12-15.

Shinde, D.A., and A.B. Ghosh. 1971. Effect of continuous cropping and manuring on crop yield and characteristics of a medium black soil. Proceedings of international symposium on soil fertility evaluation, New Delhi. I: 905-916.

Smith, D.M. 1986. The practice of silviculture. 8th ed. John Wiley and Sons, New York.

Smith, R.M., G. Samuels, and C.F. Cernuda. 1951. Organic matter and nitrogen build-ups in some Puerto Rican soil profiles. Soil Science 72:409-427.

Tan, K.H. 1984. Andosols. Van Nostrand Reinhold Company, New York.

Tans, P.P., I.Y. Fung, and T. Takahashi. 1990. Observational constraints on the global atmospheric CO_2 budget. Science 247:1431-1438.

Tarrant, R.F. and R.E. Miller. 1963. Accumulation of organic matter and soil nitrogen beneath a plantation of red alder and Douglas-fir. Soil Science Society of America Journal 27:231-234.

Tiessen, H., R.E. Karamanos, J.W.B. Stewart, and F. Selles. 1984. Natural nitrogen-15 abundance as an indicator of soil organic matter transformations in native and cultivated soils. Soil Science Society of America Journal 48:312.

Tisdale, S.L., and W.L. Nelson. 1975. Soil fertility and fertilizers. Macmillan Publishing Co., Inc., New York.

Uhl, C., and I.C. Guimaraes Vieira. 1989. Ecological impacts of selective logging in the Brazilian Amazon: A case study from the Paragominas region of the State of Para. Biotropica 21:98-106.

U.S. Congress, Office of Technology Assessment. 1991. Changing by degrees: Steps to reduce greenhouse gases. U.S. Government Printing Office, Washington, DC. Report OTA-O-482.

Van der Linden, A.M.A., J.A. Van Veen, and M.J. Frissel. 1987. Modelling soil organic matter levels after long-term applications of crop residues, and farmyard and green manures. Plant and Soil 101:21-28.

Vicente-Chandler, J., R. Caro-Costas, and E.G. Boneta. 1966. High crop yields produced with or without tillage on 3 typical soils of the humid mountain region of Puerto Rico. Journal of Agriculture of the University of Puerto Rico 50:146-150.

Vitorello, V.A., C.C. Cerri, F. Andreux, C. Feller, and R.L. Victoria. 1989. Organic matter and natural carbon-13 distribution in forested and cultivated Oxisols. Soil Science Society of America Journal, 53:773-778.

Weaver, P.L., R.A. Birdsey, and A.E. Lugo. 1987. Soil organic matter in secondary forests of Puerto Rico. Biotropica 19:17-23.

Wells, C.G, R.E. Campbell, L.F. DeBano, C.E. Lewis, R.L. Fredriksen, E.C. Franklin, R.C. Froelich, and P.H. Dunn. 1979. Effects of fire on soil. Proceedings of National Fire Effects Workshop, 10-14 April 1978, Denver, CO. Washington, DC. USDA Forest Service General Technical Report WO-7.

Whittaker, R.H., and G.E. Likens. 1973. Carbon in the biota. Brookhaven Symposium in Biology 24:281-302.

Wilde, S.A. 1958. Forest soils. The Ronald Press, New York.

Winjum, J.K., and P.E. Schroeder (ed.). 1991. Proceedings of the international workshop on large-scale reforestation, 9-10 May 1990. U.S. Environmental Protection Agency, Corvallis, OR.

Woodwell, G.M., R.H. Whittaker, W.A. Reiners, G.E. Likens, C.C. Delwiche, and D.B. Botkin. 1978. The biota and the world carbon budget. Science 199:141-146.

WRI (World Resources Institute). 1990. World resources 1990-91. Oxford University Press, New York.

Review of Soil Organic Matter Research in Puerto Rico

Miguel A. Lugo-López

Abstract

There are considerable reserves of organic matter and nitrogen in the soils of Puerto Rico. Conservation and wise utilization of these resources appears to be a worthy goal for enhancing crop production while simultaneously maintaining soil fertility and addressing critical environmental concerns.

Data from field, greenhouse, and laboratory experiments are presented on the effect of crop and industrial residues on properties, production potential, and erosion control of several tropical soils at more than 20 different sites that represent the major land resources of Puerto Rico. More than 100 different soil series were sampled from the various ecological regions.

The evidence reported tends to show that the addition of low N organic matter to Oxisols and related soils for the purpose of raising their organic matter content is of doubtful value, since organic matter levels remain unaffected and crop yields are not improved. However, there is a marked response to low N organic matter sources in other soils, resulting in significant increases in the soil organic matter levels. Soil-water movement and availability were favorably affected after five years of continuous organic matter build-up as contrasted to depletion processes caused by yearly burning of crop residues. Significantly increased yields may be attributed to the increased organic matter levels of soils.

The response of food crops to legume green manure additions may well be the result of increased and continuous N supply available to the plants that replace the legume crops. Crop rotation experiments involving corn and legumes suggest that sources of N, other than the applied fertilizer N, are available. The high levels of production attained for relatively short periods of 12 and 14 months would not have been possible unless a substantial amount of N became available from sources other than the fertilizer. Mineralization of soil organic matter and root residues might be playing an important role in this respect.

The increase in yields attributable to cropping and soil management practices can be traced, in most cases, directly to the increase in nutrient availability from mineralization of the soil organic matter and to the beneficial influence on soil properties such as hydraulic conductivity and available soil-water supply. Laboratory studies indicate that an excellent stable soil structure develops after treatment with some organic residues. Organic matter is probably the most important single factor contributing to aggregate stability.

The evidence also points out the beneficial effects of mulching with organic residues as a soil conservation practice in Oxisols and other soils in areas of steep slopes. The value of mulching is evident from data revealing soil losses of more than 15 and 30 Mg ha^{-1} yr^{-1} from unmulched sugar cane fields and coffee groves, respectively.

It has been shown that under intensive agricultural use, soil carbon in the top 18 cm of the soil was about 30-37 Mg ha^{-1}, regardless of climatic conditions. Reduced intensity of agricultural use results in an increase of soil carbon on the order of 0.3-0.5 Mg ha^{-1} yr^{-1} over a 40-year period. Low C/N ratios suggest that intensively used soils may be stable in their nutrient retention capacity. The role of these soils as atmospheric carbon sources has probably been overestimated while their potential role as atmospheric carbon sinks has been underestimated.

INTRODUCTION

The importance of soil organic matter build-up and maintenance in the tropics has been widely recognized (14, 22). However, its role has often been overstated because of the assumption that organic matter levels are low in all tropical soils as compared with soils from the temperate regions. Smith et al. (35) have shown that the organic matter levels of the soils of Puerto Rico are at least as high as those of many cultivated soils of the temperate zone. The influence of organic matter levels upon soil properties, erosion control, and crop yields has been pointed out repeatedly (15). The utilization and conservation of soil organic matter appear to be worthy goals for soil protection, crop production, and fertility maintenance. As a soil conservation practice on steep slopes, mulching is beneficial and necessary if a permanent agriculture is to be developed (38).

In recent years, with the greatly increased cost of N fertilizer putting it beyond the means of most farmers in developing nations, more attention has been given to alternate sources of N in crop production. One of the apparently feasible alternatives is the adequate use of crop residues. To evaluate this possibility, a reexamination of the amount of N which can be supplied from the mineralization of crop residues and other organic products is essential, especially under conditions in the tropics where information is scarce. Of particular importance is the role of edible legumes in a rotation to supply food and provide N to a subsequent crop.

The N-supplying power of many tropical legumes and, particularly, of non-legumes has been partially assessed. Little is known about the factors that may modify this N supplying power under tropical environments, however. The total N content and degree of maturity of legumes and non-legumes to be plowed-under greatly influence the N supplying power. This is a reflection of the amount and nature of the C and N compounds in the plant. The less mature the material, the easier it is for the N mineralizing microorganisms to decompose it, since the nature of the C and N compounds is more favorable and renders available N to the succeeding crop.

This paper, reviewing research conducted in Puerto Rico over a span of 50 years, assesses the role of organic matter in minimizing the deterioration of soil properties, enhancing soil nutrient supplying potential, and controlling erosion in tropical soils. It brings together in a single report the results of work conducted throughout the 50-year period and published in various local and outside publications. Selected data are reexamined and evaluated.

Effect of Organic Matter on Soil Properties

Data on soil properties influenced by crop residues, addition of organic materials, and use of industrial wastes were taken from numerous laboratory, greenhouse, and field experiments conducted over the years on various soils: Catalina clay (Rhodic Hapludox), Vega Alta silty clay (Plinthic Paleudult), Coto clay (Typic Hapludox), Bayamón silty clay (Typic Hapludox), Lares clay (Aquic Hapludult), Fajardo clay (Aquic Paleudalf), Santa Isabel clay (Typic Pellustert), Fé clay (Typic Chromustert), Guánica clay (Typic Pellustert), Toa clay (Fluventic Hapludoll) and Humatas clay (Typic Haplohumult) (21).

Bonnet et al. (4) studied the long-term effect of sugar cane trash handling on the organic matter content of Catalina clay. The data revealed organic matter levels of 3.74% irrespective of whether the trash was used as mulch or burned. Mulching with trash, although effective as a soil conservation practice, did not affect the organic matter levels of this Oxisol. Values for soil N showed an identical trend.

Landrau, Jr. et al. (10) conducted another trash handling experiment at Isabela on the northwest coastal plains over a period of six years. The soil was a Coto clay (Typic Hapludox), a yellowish brown Oxisol derived from highly weathered clay sediments and some limestone residues. It is highly porous and has good physical structure, but has moderately low fertility. Treatments tested were as follows: trash burned, trash aligned, trash aligned and clean banks furrowed, and trash left undisturbed over the soil surface. Bulk and core samples were taken for physical and chemical analyses after harvesting the sixth crop. The data showed no significant differences in organic matter and N content between plots where the trash had been burned for five consecutive years and those where it had been returned to the soil. Water retained at low tensions was around 40% in all cases.

Landrau and Samuels, Lugo-López et al. and Samuels et al. (11, 20, 31) reported data from a third trash handling experiment conducted at Río Piedras on the north humid coast of the Island. The soil was a Vega Alta sity clay (Plinthic Paleudult) of moderate fertility. The trash was handled yearly after each harvest in each of three ways: burned, buried, and aligned in alternate banks. Infiltration tests were run in the field, and bulk and core samples were taken for laboratory analyses after the seventh sugar cane crop was harvested. After six years of different trash handling, the mean organic matter content of the soil from the plots where the trash had been burned was significantly lower (1.42%) than from the plots where it had been aligned (1.70%) or buried (1.82%). No significant differences were observed in N content, and the C/N ratios were narrow in all cases. Water movement was slower in the trash-burned plots, 3.56 versus 6.05 cm h^{-1} at the eighth hour. The upper three-inch layer of soil retained less water at low tensions than did the soil from plots treated otherwise (50 versus 44%).

Another organic material commonly applied to the soil is filter press cake or filter press mud, which is a byproduct from the sugar mills. One experiment at Arecibo in northern Puerto Rico was established on a Bayamón silty clay (Typic Hapludox), an acid, deep Oxisol of the coastal plains derived from weathered limestone and clayey deposits. The soil had very favorable physical conditions, but was low in fertility. A second experiment was established at Corozal, in north-central Puerto Rico, on a level Lares clay (Aquic Hapludult), a moderately friable soil occurring on terrace formations and derived from material washed from the Lower Tertiary clays and shales. The same experimental design was used in both experiments. Treatments were as follows: filter press cake was applied during land preparation at the rate of 70 Mg ha^{-1} and a 12-6-10 fertilizer was applied after planting pineapples at a rate of 3,360 kg h^{-1}. No filter press cake was used in another treatment. Following harvest—when pineapple plants were some 18 months old—bulk and core soil samples were taken for laboratory studies (8, 15, 16).

The organic matter content of the Oxisol (2.38%) was not affected by the addition of 70 Mg ha^{-1} of filter press cake. On the Ultisol, however, the organic matter level of the soil increased significantly in response to treatment (2.26% and 2.81% at 0 and 70 Mg ha^{-1}, respectively). Nitrogen levels remained unaffected at both locations. Lugo-López et al. (23) found that water retained at low tensions increased significantly in the Ultisol in response to the corresponding increase in soil organic matter (36 versus 40%).

The use of green manure crops as a means of increasing organic matter levels and crop yields has been the focus of numerous studies (5, 16, 19, 22, 30, 31, 37). Field experiments were conducted at Mayagüez (Catalina clay: Rhodic Hapludox) and Río Piedras (Fajardo clay: Aquic Paleudalf) to test the influence of legumes on food crop yields and soil properties. The soil at Mayagüez was a deep reddish-brown, open, porous, Oxisol at a 40 to 50% slope (4, 5). At Río Piedras it was a medium heavy Fajardo clay, an Alfisol derived from volcanic shales. In the first set of experiments the following crop rotation was used: two legume crops, one sweet potato crop, two legume crops, and two corn crops. The legume crops were limed and fertilized with P. The second corn crop was fertilized with K and P. The equivalent of 20 to 27 Mg ha^{-1} of velvet bean green manure was incorporated into the soil from the two crops of velvet beans before planting sweet potatoes and corn, respectively. Soil samples were taken to a depth of 10.2 cm after the first corn crop (sixth on the rotation) was harvested. No increase in the soil reserve of organic matter could be attributed to treatment: for the Oxisol, it was 1.30% when no green manure was incorporated into the soil and 1.90% when 20-27 Mg ha^{-1} were incorporated; the Alfisol showed 1.80% in both treatments.

Bonnet and Lugo-López (5) conducted another experiment at both locations to find the optimum level of velvet bean to be used as a green manure. Prior to planting the legume, the plots were fertilized with P. After harvesting the legume crop, the following treatment differentials were imposed: 0, 11 and 22 Mg ha^{-1} of green manure, respectively, at Mayagüez; a fourth treatment with 55 Mg ha^{-1} of green manure was included at Río Piedras. Two corn crops followed the velvet bean crop at Río Piedras and one at Mayagüez. Each corn crop received K fertilizer. Soil samples were taken at the

2.5-15 cm depth from each plot after the second crop was harvested at Río Piedras. No significant increases in organic matter attributable to green manure applications were observed (3.8%, average of all four treatments). N content followed the same trend. Although no soil data are available for the Mayagüez site, it is speculated that probably the same situation prevailed.

Wahab and Lugo-López (40) conducted exploratory studies in an attempt to determine the mode of action of organic matter on the immobilization of Al in an acid Ultisol. Ground coffee leaves and pangola grass were evaluated against various rates of $Ca(OH)_2$. Regression analyses showed correlation coefficients of over 0.91 when $Ca(OH)_2$ was the independent variable and exchangable Al, pH and dry matter production were the dependent variables. An overall examination of data revealed that acid Ultisols, high in exchangeable Al, inhibit plant growth and limit yields. The addition of coffee leaves decreases soil acidity and soil exchangeable Al. Coffee leaves were apparently more effective than pangola grass in inhibiting Al toxicity. Organic matter might alleviate Al toxicity since it increases cation exchange capacity, and possibly the organic matter has a chelating effect on Al.

Laboratory studies conducted by Pérez-Escolar (26, 27, 28) revealed that blackstrap molasses and rum distillery slops were effective on the reclamation of the highly saline-alkali Fé clay (Typic Chromustert) in southwestern Puerto Rico. Around 14.4 ha-cm of distillery slops and diluted molasses were sufficient to lower the conductivity of the soil-saturation extract from 67 mmhos cm^{-1} to less than 3, and the exchangeable sodium percentage from 43 to less than 1%. An excellent stable soil structure was found in all molasses and slops treatments when compared with the highly dispersed controls (25).

Further work by Pérez-Escolar (27) was conducted to evaluate the effect of molasses and distillery slops in conjunction with sulfur for the reclamation of a saline-sodic soil (Fé clay: Typic Chromustert) and a sodic soil (Guánica clay: Typic Pellustert). Hydraulic conductivity values were markedly increased as a result of the sulfur-slops and sulfur-molasses treatment, and removal of harmful exchangeable sodium was possible throughout the growth of three corn crops. This was probably because of better water movement and the fact that more Ca ions were brought into circulation to displace adsorbed Na ions.

Pérez-Escolar (28) used infrared spectroscopy to analyze blackstrap molasses, rum distillery slops, the active fractions of the slops, <2μ clays of the two poorly drained soils, and on the complexes formed between organic materials and the clays of Guánica and Fé soils. X-ray spectroscopy of the <2μ clays and of the complexes formed with the organic materials was also done. Under X-rays, characteristic peaks for hydroxyl, methyl, amino, methoxy, carbonyl, and ketonic groups were observed. The spectra of the clays showed peaks which are attributed to hydroxyl, bonded and unbonded, adsorbed water, silica tetrahedra, and aluminum octahedra. Hydrogen bonding occurred between the exposed hydroxyl groups of the clay crystals and the molasses, slops, and their active residue. There was no shift in the 2Θ angle of diffraction of the expanding-lattice clays, indicating that there was no adsorption in the interlamellar spaces. The adsorption was possible at the edges of the crystals. The finding was strengthened by the fact that, rather than a decrease in cation exchange capacity of the expanding lattice clays, there was a slight increase.

Pérez-Escolar presented information obtained from laboratory studies which provide insight into the nature of the soil aggregating and stablizing agents present in rum distillery slops (28). The main agents were constituents of the 80% alcohol-insoluble fraction of the rum distillery slops as shown by determining their soil-aggregate-stability activity. Fractionation of the active material indicated that 6% of it was a monnose-bearing polysaccharide, 7% was protein, and the remaining 87%, the main constituent, was a caramel. The latter results from the sucrose recovery process at the sugar factory and is not attacked by yeast in the molasses fermentation process (28).

Data from Pérez-Escolar and Lugo-López (29) show that organic matter has a very definite influence as a cementing agent among clay particles in the Catalina (Rhodic Hapludox) and Humatas (Typic Haplohumult) soils. In the Catalina soil, water-stable aggregates were 90.2, 85.3, and 71.7% in the 5-3, 3-2, and 2-1 mm size aggregates, respectively. For the same size aggregates the corresponding values in the Humatas soil were 79.6, 71.7, and 68.1 mm. The high stability of aggregates in these soils can be attributed to the interrelationship between soil organic matter and iron oxides. This fact was shown by the low clay values obtained when organic matter was not removed by pretreating the soil with hydrogen peroxide prior to determining particle size distribution. Pretreated aggregates of all three sizes (5-3, 3-2, and 2-1 mm) in the Catalina soil contained 60-62% clay; untreated ones, 32-34%.

The results of the work of Smith and Cernuda (34), based on air-slaking and on water-drop impact, show that surface soil macroaggregates are much more stable than those from subsoils when both are subjected to conditions common at exposed surfaces. The differences are associated with the relatively high organic matter contents of surface soils.

Further work by Lugo-López and Juárez, Jr. (17) with the Aguirre, Guánica, Santa Isabel (all Typic Pellusterts), Fraternidad and Fé (both Typic Chromusterts), and Jácana (Vertic Haplustoll) soils revealed a highly significant correlation between aggregate stability and soil organic matter content. Thus, it can be stated that organic matter is probably the most important single agent determining aggregate stability in these soils. However, in Oxisols and Ultisols the aged R_2O_3 and the Al and Fe hydroxyl coatings are probably more effective.

Edminsten (7) observed, from closeup photographs of the structure of soils in the vicinity of El Verde Rain Forest, that organic matter from constant additions of detritus maintains a slime coating around the complex crumb aggregates. He believes that Oxisols such as those of the El Verde Forest may lose this structure if they are exposed to the sun and rain of the tropical climate.

It has been shown by Abruña and Smith (2) that the removal of organic matter has a significant but not a major effect on exchange values of Oxisols. Free oxides, on the other hand, are evidently blocking a significant amount of exchange. Their removal increased the measured exchange capacities in two depths of Catalina clay, whereas the loss of organic exchange would be expected to cause a consistent decrease if this was the only factor involved.

Abruña and Vicente-Chandler (1) reported on the organic matter activity in terms of exchange capacity of some typical soils of Puerto Rico. The exchange capacity of the organic matter varied rather widely, but was generally between 100 and 150 meq/100 gm of soil. On the average, it accounted for about 25% of the total exchange capacity of the soils. The organic matter removed by flotation had the highest exchange capacity and the more readily oxidizable portions generally appeared to be the most active. This suggests the importance of conserving the portions of soil organic matter that are more readily lost. A considerable portion of the soil organic matter was extremely resistant to oxidation, had a narrow C/N ratio, and apparently little exchange capacity. This suggests a close association between the organic matter and the inorganic soil colloids (2). The marked resistance to oxidation of a considerable portion of the organic matter may partly explain the high contents found even in continously cultivated soils of Puerto Rico.

Lathwell et al. (9) evaluated the N-supplying power of representative Oxisols and Ultisols of Puerto Rico as measured by continuous cropping in the greenhouse. The soils contained substantial quantities of inorganic N as extracted by 1N KCl. In addition, about one-half of the inorganic N found in these soils was present as exchangeable NH_4, with little variation among soils. The amount of N extracted by the first four crops varied widely among soils. These crops were grown consecutively without drying the soils between crops. These differences in supply of N decreased with cropping until, in the fourth crop, much smaller soil differences were found. Although the ability of these soils to supply N declined over time, the quantities of N released to the fourth crop were nevertheless substantial. Lathwell et al. (9) postulated that "Since several of these soils released large quantities of N to the first two crops, under field conditions these soils would likely release sufficient N to meet the N requirements of all but the most demanding crops."

The effect of seasonal changes in mineralizable N was noted. In the field, a flush of inorganic N release often results upon wetting these soils following a dry season. The results obtained in plots by Lathwell et al. (9) also produced a flush of available N subsequent to a drying period. In 9 out of 10 soils, the quantity of N removed by crop 5 (from 14 to 51 mg/kg of soil) was more than twice the quantity removed by crop 4 (from 7 to 16) and in most instances was greater than the amount removed by crop 3, i.e., from 8 to 22.

The quantity of N mineralized in all soils increased with the length of the incubation periods. Data corresponding to a Catalina soil (Rhodic Hapludox) showed that mineralized N increased from 64 to 136 ppm when the incubation period was extended from 2 to 16 weeks. The correlation between N mineralization and N uptake by the first four crops or by all five crops was extremely high. Furthermore, the length of the incubation period had little effect on the correlation obtained. Thus, this incubation procedure appears to be highly useful in predicting the ability of these tropical soils to supply N.

In 1986, Lugo et al. (12) published the results of their study testing the assumption that the organic matter content of tropical forest soils is oxidized to atmospheric carbon dioxide when they are converted to agricultural use. They resampled some of the sites studied by Lugo-López (13) between 1944-46 as well as other locations. Results showed that under intensive agricultural use, soil carbon in the top 18 cm of soil was about 30-37 Mg ha^{-1}, regardless of climatic conditions. Reduced intensity of agricultural use resulted in an increase in soil carbon of 0.3-0.5 Mg ha^{-1} yr^{-1} over a 40-year period.

Relatively fast rates of soil carbon accumulation were observed (12). They postulated that rates of soil carbon accumulation were inversely related to the sand content of soils. The relations between rates of soil carbon accumulation and climate or soil texture were better defined at higher soil carbon content. Soils under pasture accumulated soil carbon and often contained similar or greater amounts than adjacent mature forest soils (60-150 Mg ha^{-1} in the top 25 or 50 cm). Soils in moist climates exhibited greater variations in soil carbon content with changes in land use (both in terms of loss and recovery) than did soils in dry climates. The observed resiliency of these soils suggests that their role as atmospheric carbon sources has been overestimated, while their potential role as atmospheric carbon sinks has been underestimated.

Odum (24) summarized studies on the organic matter content in forest soils of Puerto Rico below loose litter. Values at El Verde Rain Forest were lower (8% at 2-15 cm and 1% at 15-30 cm depths) than those of the Colorado montane thicket (11% at 2-15 cm and 8% at 15-30 cm) and elfin forests (65% at 2-15 cm and 48% at 15-30 cm). The order of magnitude of organic matter in the upper soil is equal, however, to that in trunks and large roots.

In 1989, Sánchez-Irizarry (32) reported on her study of three Ultisols in Puerto Rico, two from pine plantations and the other from a mahogany plantation with natural secondary forest of similar age. Conversion of secondary forest to pine plantations did not significantly affect total organic matter, bulk density, or effective cation exchange capacity in the 0-15 cm depth layer. However, pH decreased from 4.8 to 4.5 while Mn in solution (106 to 172 mg kg^{-1}), titrable acidity (1.7 to 4.4 c mol(+)kg^{-1}) and Al saturation (24 to 61.5%) all increased. When compared to an adjacent natural secondary forest stand, the mahogany plantation was found to have a higher bulk density (0.89 versus 0.71 g cm^{-3}) and less organic matter (5.2 versus 8.4%). The values for pH in 1N KCl and Mn in solution were also significantly higher ($p=.01$) in the mahogany plantation. Titrable acidity in the mahogany plantation was 0.5 versus 4.0 c mol kg^{-1} for the secondary forest; the Al saturation was 4.7 versus 40.4%. Results suggested that the composition of the organic matter must be assessed before ascertaining changes in soil fertility due to land use changes from natural forest to plantation.

Lugo-López (13) developed regression equations to predict soil moisture content on the basis of clay content and soil organic matter content of soils. In some soils, a 10% increase in clay content can produce a corresponding increase in field capacity of nearly 200%. However, for some Oxisols, like Nipe (Anionic Acrudox), Catalina, and Coto, and maybe for other soils, too, the regression equations do not satisfactorily predict moisture contents on the basis of clay content alone. The functional relationships between soil moisture and organic matter were not as precise as those obtained with clay. When the organic matter increased from 1 to 2% there was an increase in the water retained at field capacity; additional increases in organic matter were ineffective. Data from the Soil Conservation Service (36) revealed that the moisture content at 1/3 bar of a Coto soil with 70% clay was 28%; of a Nipe soil with 60% clay, 34%; of a Catalina soil and a Fraternidad soil with 60% clay, 40%.

Influence of Organic Matter on Crop Yields

Data on soil productivity were obtained from a large number of field and greenhouse experiments involving sugar cane trash handling techniques (4, 10, 11, 15, 18, 20, 31); applications of filter press cake (8, 16), bagasse (6), garbage compost (18), and commercial organic products (6); and the incorporation of legume and non-legume crop residues (22, 30, 37).

An analysis of the data shows that continuous burning of sugar cane trash in Oxisols does not cause any measurable decline in sugar yields. On the other hand, after five years of continuous cultivation on an Ultisol at Río Piedras the same treatments produced significant differences in yields. The aligned treatment was significantly better at the 5% level than other treatments for the fifth ratoon crop. This increased to significance at the 1% level for the sixth ratoon crop (11, 30).

No significant difference in pineapple yields attributable to the application of 70 Mg ha^{-1} of filter press cake was measured in Oxisol near Arecibo. However, on the Corozal Ultisol, yield increases of nearly 12 Mg ha^{-1} of fruit could be attributed, at least in part, to the application of 70 Mg ha^{-1} of filter press cake (8).

Data from a field experiment where bagasse, filter press cake, and a commercial organic material were incorporated into a Vertisol show that bagasse depressed yields of corn in a highly significant way. This seems to indicate competition from bacteria decomposing the bagasse since the C/N ratio must be very wide. The use of filter press cake at the rate of 88 Mg ha^{-1} outyielded bagasse at 44 and 88 Mg ha^{-1}, the commercial organic material at the higher rate, and the check. No significant effects were measured on the bean and sweet potato crops planted about 5 and 13 months, respectively, after establishing the treatment differentials (6).

Data obtained from a greenhouse experiment on an Alfisol permitted the evaluation of municipal garbage compost as compared with filter press cake and fertilizers (19). The content of P and K were higher in the garbage compost than in the filter press cake, but the former was slightly lower in organic matter. They both had about the same N level. Additions of garbage compost and filter press cake increased sorghum yields in the absence of inorganic fertilizers from less than 14 g/pot in the controls to approximately 32 and 24 g/pot, respectively. However, when N, P, and K were applied at the rate of 110 kg ha^{-1} each, the application of either compost or filter press cake did not increase yield significantly.

The conservation of soil N and organic matter through the use of legumes, non-legumes, and organic materials has received considerable attention in Puerto Rico. The results obtained provide important reference points.

Field data from an Oxisol at Mayagüez and an Ultisol at Río Piedras, in experiments designed to test the influence of legumes on food crop yields showed significant yield increases at both locations for sweet potatoes and corn, which could be attributed to treatment. Results suggested that perhaps the increased yields were attributable to an increased N supply through the activity of the legume (15). This N was used quickly by the growing crops. The increased rapid release of N under tropical conditions has been emphasized by Vicente-Chandler (39). His data indicated that a legume or a legume-grass mulch can provide an economical supply of N for plant growth.

Further evidence was obtained from the same soils both at Mayagüez and Río Piedras. In the Oxisol, 11 and 22 tons of green manure notably increased corn yields. No significant differences between treatments were found by Bonnet and Lugo-López for the two corn crops on the Ultisol, but a consistent trend toward increased yields with increased green manure supply was observed (5).

Various sets of crop rotation experiments were conducted on three soils: a sandy Oxisol (Bayamón), a clayey Ultisol (Humatas), and a clayey Oxisol (Catalina). The first set of rotation experiments followed a split plot design where the main plots were three rotations: soybeans, corn, corn; corn, corn, corn; and fallow, corn, corn. The subplots included two treatments for the two corn crops following the initial crop: 0 and 110 kg ha^{-1} of N applied as urea. After harvest of the first corn and soybean crops, the corn roots, soybean stover, and weed fallow were plowed under some two weeks before planting the second crop. The data obtained show that corn without fertilizer N following soybeans yielded substantially more than corn following corn or fallow in four out of five crops. Mean differences were highly significant.

A second set of rotation experiments was conducted on an Oxisol (Bayamón series) at Manatí and an Ultisol (Humatas series) at Corozal (22). Again, the rotation experiments followed split-plot designs. The main plots were four rotations: soybeans, corn; winged beans (*Psophocarpus tetragonolobus*), corn; mung beans (*Phaseolus radiata*, var. aureus), corn; and corn, corn. The subplots included two treatments for the corn crop following the initial crop: 0 and 67 kg ha^{-1} of fertilizer N applied as urea when the plants were one month old. At the Corozal site, corn yielded substantially more following soybeans, mung beans, and winged beans than following the initial corn crop. It should be emphasized that the initial corn crop received 110 kg ha^{-1} of fertilizer N while the legume crops did not receive fertilizer N. This was not the case at the Manatí site, except for corn following mung beans. At both sites, some 80% of the maximum corn grain yields obtained when fertilizer N was applied could be obtained when no N was applied, especially at the clayey Ultisol, when following the legumes.

Mulching can be of great value in tropical agriculture (38). The application of coffee pulp mulch sharply increased yields of strip-cultivated coffee from an average of 978 to 1,549 kg ha^{-1} (39). Coffee pulp was superior to grass or black plastic mulch, which did not increase yields of strip-cultivated coffee. Coffee pulp mulch probably increased yields through a combination of factors, i.e., it increased available water (10 cm versus 4 cm when unmulched), kept the surface soil cool, and provided a continuous additional supply of nutrients.

Role of Organic Matter in Soil Erosion Control

Smith and Abruña (33) reported data on soil erosion control obtained through a series of experiments conducted *in situ* on a Catalina clay (Rhodic Hapludox), a deep, reddish-brown Oxisol at a 40 to 50% slope, and on a Múcara clay (Vertic Eutropept), a moderately deep Inceptisol on a 62% slope at Mayagüez, in western Puerto Rico. Water and soil losses were determined by volume and weight measurements of runoff and soil collected in sheet metal tanks. Runoff and erosion were measured under various conditions: different crops or crop sequences, cultivation practices, mulching and bare fallow soil, both natural and desurfaced.

Mean annual rainfall was 1,854 mm during the experimental period. Evaporation exceeded rainfall from December to May. Growth of all crops was sparse during these five months and runoff was slight even in the bare fallow plots. However, plant growth and yields were high during the seven months of heavier rainfall. The highest rainfall measurements were recorded in July, August, and September; the rains in those months and in May also registered the highest average intensities. At the other extreme, January and February had the lowest rainfall amounts and the lowest intensities. During June, rainfall was more stable and better distributed. This is probably the reason why soil losses on fallow soil were somewhat less in June than in May. In March and May high volumes of rain accounted for much of the water and soil losses measured during those months.

Crop rotation reduced soil losses to about 10% of that which occurred on the desurfaced plots. Water losses were also reduced from 584 to 127 mm. The bunch grasses, such as Guinea grass (*Panicum maximum*) provided less soil protection than the stoloniferous types. Molasses grass (*Melinis minutiflora*), during a three-year period, provided excellent soil protection. In general, the reduction in soil losses under grass cover was striking.

It has been suggested that sweet potatoes (*Ipomoea batatas*) may give the best control of any of the cultivated crops on steep soils (14). However, measured total losses under sweet potato cover were still too heavy: two metric tons of soil were lost in one year and more than seven in another, most of which loss probably occurred before the vines and foliage covered the soil and during harvesting. Mechanical soil losses are likely to be heavy at harvest time. For this reason, sweet potato cannot be rated as a soil-conserving crop until completely established and covering the surface soil. Data on crop sequences show the fallacy of considering legume crops as necessarily soil-conserving. They provide effective control only after a good stand and ground cover have been attained. In many cases the ground is left open and serious losses are liable to occur most of the time with legume crops as well as with other cultivated crops. For example, in a given year, the legume plots lost 74 tons of soil (Catalina clay) when planted to pigeon peas (*Cajanus cajan*) followed by jack beans (*Canavalia* sp.). A crop sequence like that clearly is not soil-conserving. On the other hand, tropical kudzu (*Pueraria phaseoloides*), because of its growth habit, is a legume that covers the ground and reduces soil and water losses to a minimum.

Mulches are very effective in reducing soil losses (from 15,047 to 2,738 kg ha^{-1}) and water losses (from 150 to 38 mm). These dramatic differences were recorded in spite of the fact that all plots were cropped in a rotation involving cowpeas (*Vigna unguiculata*), sweet corn, and squash, which are not good soil-conserving crops (23).

Data from plots planted to coffee in a Múcara soil (Vertic Eutropept) indicate that individual terraces had little if any effect on soil and water losses. With or without terraces 25 mm of runoff removed 673 kg ha^{-1} of soil. However, when the ground cover was removed, 25 mm of runoff carried away 6,730 kg ha^{-1} of soil. In a given year, actual losses were 271 mm of water and 30 tons of soil. With the ground cover cut clean and removed, coffee culture appears to be as destructive as cultivated cropping unless coffee is planted in hedges that offer an effective barrier against erosion. It must be noted that on Ultisols and Oxisols, where coffee is normally grown, actual soil losses are lower since these soils are less erosive than the Múcara soil. After a year, the cleaned plots lost less soil and water, but much more than before cleaning. After two years, the losses were still somewhat high, but by the third year they were back to the same amount as when the plots had full ground cover. The trend of losses indicates that two full years or more are required to build up the same degree of soil protection as that which exists prior to cleaning and removal of ground cover (33).

A trash-handling experiment was conducted in western Puerto Rico (Mayagüez) to evaluate the soil conservation effects of mulching with sugar cane trash as compared with burning trash (4). The soil was a Catalina clay (Rhodic Hapludox), near the same site where the runoff plots were established. Four crops of sugar cane were harvested. When the residues were returned to the soil as a mulch, erosion losses were little more than under good grass cover, i.e., 1.50 Mg ha^{-1}. This could probably be tolerated indefinitely on this deep, open, porous Oxisol. When the cane trash was burned, however, soil losses of nearly 17 Mg ha^{-1} occurred yearly. This is considered excessive for permanent agriculture.

In 1967, Barnett et al. (3) measured soil losses for selected cropping systems using artificial rainfall techniques on three soils of Puerto Rico. The soils were Humatas clay (Typic Haplohumult), Juncos silty clay (Vertic Eutropepts), and Pandura sandy loam (Typic Eutropepts). Artificial rain was applied at 6.4 cm h^{-1} for 60 minutes (Storm 1), followed ten minutes later by 12.7 cm h^{-1} for 60 minutes (Storm 2). Storms 1 and 2 were combined and designated as Storm 3, thus extending the range of storms represented from less than two- to more than 500-year frequency storms. Cropping systems tested were fallow, conventional tobacco, mulched-tilled tobacco, tobacco in grass strips, pangolagrass (*Digitaria decumbens*), and pangolagrass with all aboveground parts removed. Slopes ranged from 26 to 46%; plots were 10.7 m long. Test areas had been in grass for several years. Final infiltration rates were 0.9, 3.7, and 6.2 cm h^{-1} for Juncos, Humatas, and Pandura, respectively. The low infiltration rate of the Juncos soil is misleading. Actually, most of the rainfall infiltrated this soil but returned as interflow at the lower end of the plots. Average erosion losses on 26 to 46% slopes were 1.7, 6.0, and 6.7 Mg ha^{-1} for Juncos, Humatas and Pandura soils, respectively. All soils were resistant to erosion due to their high degree of aggregation and, in part, to the lasting effect of the grass grown in previous years. Soil losses attributable to the various treatments for the Humatas clay, Storm 3, ranged from 0.7 (full sod) to 11 Mg ha^{-1} when the pangolagrass tops were removed. Tillage increased water storage capacity in the soil and reduced runoff in the tobacco with mulch tillage and tobacco in grass strips. All cropping treatments increased erosion when compared with fallow, pangolagrass full sod, and tobacco with mulch tillage. The opposite was true for the Juncos and Pandura soils: all cropping systems reduced erosion when compared to fallow.

In general, the rates of soil loss for the fallow soil and tobacco with conventional tillage gradually increased during Storm 1, peaked at a high rate shortly after Storm 2 began, and then declined to the end of that storm. For the tobacco with conventional tillage, rates of soil losses were 9.40, 3.40, and 0.31 Mg ha^{-1} per 2.54 cm of runoff for the Pandura, Humatas and Juncos soils, respectively. Soil loss increased more than tenfold with the removal of the above ground parts of pangolagrass. This fact dramatizes the effectiveness of ground cover for erosion control. Soil losses were high, with 1.68 and 9.13 Mg ha^{-1} from storms 1 and 2, respectively, where the grass tops were removed and the bare soil was exposed.

Discussion

This comprehensive review confirms that there is a rather high reserve of soil organic matter and N in the soils of Puerto Rico (14, 35). The predominant factors in the organic matter balance are mostly climatic or, perhaps, climatic and biotic. Thus, Oxisols, which are rather old soils, have probably reached a level of equilibrium with the surrounding ecological factors and, under natural conditions or conservation-minded farming, approach the maximum retention of organic matter that they can attain. Aeration and leaching, which are favored by the physical conditions of Oxisols, are the principle controlling factors.

The relatively fast observed rates of soil carbon accumulation will modify model predictions about the flux of carbon from the soil to the atmosphere. Results suggest that only the cultivated soils are consistent sources of carbon dioxide; pastures may be sinks. Furthermore, it is possible that even under cultivation the period of time during which soil carbon is oxidized to carbon dioxide is limited by the fraction of the labile organic carbon content.

The results reviewed here have an important bearing on any discussion of the fertility of tropical soils. The capacity of tropical forest soils to conserve and enhance organic matter has positive implications for the conservation of soil nutrients. The C/N ratios of soils under intensive use are typical of stable soils. These stable C/N ratios can be attributed to the abundance of nitrogen fixed by weeds and successional components of sites.

The evidence reviewed in this paper tends to show that the addition of low N organic matter sources to Oxisols for the purpose of raising their organic matter content is of doubtful value, since organic matter levels remain unaffected and crop yields are not improved. Data from a field of Coto clay (Typic Hapludox) that has been under sugar cane cultivation for more than 20 years show an organic matter level of approximately 3%. Subsequently, a section of that field was used to grow clean-cultivated crops for four years, while the rest was planted to cane continously. The levels of organic matter remained unaffected. Fertilization and liming, however, are essential practices for most crops to be raised profitably on these soils (18).

The use of garbage compost, bagasse, and other low N organic sources which are expensive and bulky is questionable (6, 19). A better utilization of farm resources can be of great help in soil organic matter maintenance and build-up in many Puerto Rican farms. Roots provide a vast supply of organic matter. The use of grasses and legumes in suitable rotations, as well as green manure and cover crops, will be of great assistance where large amounts of organic residues are not normally available.

The evidence also points to the beneficial effects of mulching with organic residues as a soil-conservation practice in Oxisols and Inceptisols on rather steep slopes, if a permanent agriculture is to be maintained. Losses from fields where sugar cane trash was burned increased at least tenfold over those from fields where it was used as a mulch. The value of mulching was dramatically exemplified by the huge soil losses—30 Mg ha^{-1}—when the ground cover was clean cut and removed from the surface soil of a Vertic Eutropept.

There was a distinct response, however, to low N organic matter sources in Ultisols which resulted in significant increases in the soil organic matter level. It must be noted that these soils were reasonably well fertilized both for the sugar cane and pineapple crops. Significant yield increases were obtained for both crops, which is probably attributable to the favorable effects of increased organic matter levels on the physical conditions of the soils. This was particularly true in the sugar cane trash handling experiment on a heavy Plinthic Paleudult where yield increases were measured only after five years of continous organic matter build-up in some plots, as contrasted to plots where depletion rather than build-up processes were favored by yearly burning of the residual cane trash.

The response of food crops in terms of yields due to legume-green manure additions to an Oxisol in Mayagüez may well be explained by the increased and continuous N supply available to the food crop plants following the legume crops. Both at Oxisol and Ultisol sites, significant yield increases of sweet potatoes and corn could be attributed to use of green manures even when no increases in the soil reserve of organic matter and N could be measured. Perhaps the increased yields were due to an increased, although limited, N supply through the activity of the legume. It can be postulated that this N was used quickly by the growing crops.

The data from more recent crop rotation experiments further suggest that sources of N other than the applied fertilizer N are available. From the first set of experiments, it should be noted that the three continous corn crops on the Humatas Ultisol, which were harvested over a period of less than 14 months, produced some 18,000 kg ha^{-1} of grain with the application of 110 kg ha^{-1} of N/crop (37). This suggests N sources other than the applied N, such as mineralization of soil organic matter or root residues. Lathwell et al. (9) evaluated the N-supplying power of 10 representative Oxisols and Ultisols of Puerto Rico by continuous cropping under greenhouse conditions. The results showed that substantial quantities of N can be removed from these soils by cropping.

In the second set of crop rotation experiments, total corn yields of 6,817 and 10,840 kg ha^{-1} were obtained on the Humatas Ultisol and the Bayamón Oxisol, respectively, for the two subsequent corn crops. On the Ultisol, 17,899 kg ha^{-1} of grain (both legume plus subsequent corn) were obtained without fertilizer N; on the Oxisol, 18,628 kg ha^{-1}. With fertilizer N the respective yields were increased to 20,239 and 21,535 kg ha^{-1} (30). These are sizeable amounts of grain for a period of less than a year. This increase would not be possible unless a substantial amount of N became available from sources other than the fertilizer.

The response in yields to cropping practices related to the management of crop residues and added organic materials can be traced directly in most cases to the influence on soil properties. There is ample evidence that significant changes in organic matter levels in soils, other than Oxisols, led to improved hydraulic conductivity and increased soil-water retention in the available water range. Laboratory studies indicate that an excellent stable soil structure was developed after treatment with residues such as blackstrap molasses and run distillery slops. The main soil aggregating and stabilizing agents were constituents of the 80% alcohol-insoluble fraction of the rum distillery slops. The value of organic matter in aggregation, acting as a cementing agent between clay particles, is well-known. Organic matter is probably the most important single factor determining aggregate stability.

Understanding the nature and properties of the soil is the key to its successful management. The adaptation of cropping practices that utilize this knowledge is fundamental to increased soil protection and improvement of soil productivity.

Conclusions

1. Intensive agricultural management systems in humid tropical climates lead to the greatest carbon accumulation rates in soils: approximately 80 to more than 200 g m^{-2} yr^{-1} over one- to 10-year periods. Comparative rates for forest systems range from 30 to 100 g m^{-2} yr^{-1}.
2. Management practices and inherent soil properties definitely affect organic carbon losses and potential carbon sequestration rates.
3. Carbon losses are quite rapid after soils are disturbed by agriculture and forestry activities, particularly in humid tropical areas where year-round warm temperatures favor high rates of organic matter breakdown.
4. Grassland ecosystems are recognized to be superior to forests in total below-ground carbon storage and may be even more productive.
5. There is a high reserve of organic matter in the soils of Puerto Rico. The major factors in the organic matter balance are mostly climatic or, perhaps, climatic and biotic. Thus, Oxisols, which are rather old soils, have probably reached a level of equilibrium with ecological forces and, under natural conditions or under appropriate conservation-minded cultivation, approach the maximum retention of organic matter that they

can attain. Aeration and leaching, which are favored by the physical conditions of Oxisols, are the main controlling factors.

6. Addition of low N organic sources for raising the organic matter content of Oxisols are of rather doubtful value since organic matter levels remain unaffected and crop yields are not improved.

7. On the other hand, distinct responses to low N organic matter sources have been observed in Ultisols which resulted in significant increases in soil organic matter levels. Significant yield increases were obtained which can be attributed to the favorable effects of increased organic matter levels on the physical conditions of the soils.

8. Roots provide a vast supply of organic matter. The use of grasses and legumes in suitable crop rotations, as well as green manures and cover crops, are of great assistance in organic matter build-up.

9. Mulching with crop residues is a valuable soil conservation practice in Oxisols and Inceptisols of rather steep slopes, if a permanent agriculture is to be maintained.

10. The yield response of food crops to legume green-manure additions may be explained by the increased and continuous N supply available to the food crop following the legume crop when no increases in the soil reserve of organic matter and N could be measured. This N was used quickly by the growing crops.

11. Recent data from crop rotation experiments indicate that sources of N other than the applied fertilizer N are available. Three continuous corn crops harvested in an Ultisol over a period of less than 14 months produced some 18,000 kg ha^{-1} of grain with the application of 110 kg ha^{-1} of N/crop. In another set of crop rotation experiments, total corn yields of 6,817 and 10,840 kg ha^{-1} were obtained on an Ultisol and an Oxisol, respectively, for the two crops subsequent to the legume. On the Ultisol, 17,899 kg ha^{-1} of grain (both legume and subsequent corn) were obtained without fertilizer; on the Oxisol, 18,628 kg ha^{-1}. With fertilizer N the respective yields increased to 20,239 and 21,535 kg ha^{-1}.

12. The favorable response of crop yields to management of crop residues and added organic materials can be traced directly to the influence on soil properties. Significant changes in organic

matter in soils, other than Oxisols, led to improved hydraulic conductivity and increased soil water retention in the available water range. An excellent stable soil structure was developed after treatment.

13. There is a close association between the organic matter and the inorganic soil colloids. A considerable portion of the soil organic matter is extremely resistant to oxidation, and has a narrow C/N ratio. The marked resistance to oxidation may partly explain the high carbon contents found even in continously cultivated soils of Puerto Rico.

Literature Cited

1. Abruña, F. and J. Vicente-Chandler. 1955. Organic-matter activity of some typical soils of Puerto Rico, Univ. P.R. J. Agri. 42(2): 65-76.

2. Abruña, F. and R.M. Smith. 1953. Clay mineral types and related soil properties in Puerto Rico, Soil Sci. 75(6): 411-420.

3. Barnett, A.P., J.R. Carreker, F. Abruña, W.A. Jackson, A.E. Dooley, and J.H. Holladay. 1972. Soil and nutrient losses in runoff with selected cropping treatments on tropical soils, Agron. J. 64: 391-395.

4. Bonnet, J.A., F. Abruña, and M.A. Lugo-López. 1950. Trash disposal and its relation to cane yield, soil, and water losses, Univ. P.R. J. Agri. 34(3): 286-293.

5. Bonnet, J.A. and M.A. Lugo-López. 1953. Effect of different quantities of velvet bean green manure on corn yields in Puerto Rico, Univ. P.R. J. Agri. 37(1): 96-101.

6. Bonnet, J.A., M.A. Lugo-López, and M. Rico-Ballester. 1957. Effect of incorporating organic materials into a clay soil of Lajas Valley on the yields of food crops, Univ. P.R. J. Agri. 61(3): 173-178.

7. Edminsten, J. 1970. Soil studies in the El Verde rain forest. Chap. H-3: p. 79-87. *In* H.T. Odum and R.F. Pigeon (ed.) A tropical rain forest: A study of irradiation and ecology at El Verde, Puerto Rico. U.S. Atomic Energy Commission, National Technical Information Service, Springfield, VA.

8. Hernández-Medina, E., M.A. Lugo-López, and H.R. Cibes-Viadé. 1953. The beneficial effect of filter-press cake on pineapple yields under field conditions, Univ. P.R. J. Agri. 37(3): 206-217.

9. Lathwell, D. J., H.D. Dubey, and R.H. Fox. 1972. Nitrogen-supplying power of some tropical soils of Puerto Rico and methods for its evaluation, Agron. J. 61: 763-766.

10. Landrau, Jr., P., M.A. Lugo-López, G. Samuels, and S. Silva. 1954. Leaving sugar cane trash undisturbed on a lateritic soil compares favorably with currently used trash-disposal methods, Univ. P.R. J. Agri. 38(1): 1-8.

11. Landrau, Jr., P. and G. Samuels. 1952. The handling of sugar cane trash I. Yields and economic considerations, Univ. P.R. J. Agri. 36(3): 240-245.

12. Lugo, A.E., M.J. Sánchez, and S. Brown. 1986. Land use and organic carbon content of some subtropical soils, Plant and Soil 96: 185-186.

13. Lugo-López, M.A. 1957. Moisture relationships of Puerto Rican soils, Univ. P.R. Agri. Exp. Sta. Tech. Pap. 9.

14. Lugo-López, M.A., F. Abruña, and R. Pérez-Escolar. 1981. The role of crop and industrial residues on erosion control, properties, and productivity of some major soils of Puerto Rico, Univ. P.R. Agri. Exp. Sta. Univ. P.R. Bull. 266.

15. Lugo-López, M.A., J.A. Bonnet, E. Hernández-Medina, P. Landrau, Jr., and G. Samuels. 1954. Soil organic-matter levels and crop yields in Puerto Rico, Soil Sci. Soc. Am. Proc. 18(4): 489-493.

16. Lugo-López, M.A., E.Hernández-Medina, H.R. Cibes-Viadé, and J. Vicente-Chandler. 1953. The effect of filter-press cake on the physical and chemical properties of soils, Univ. P.R. J. Agri. 37(3): 213-223.

17. Lugo-López, M.A. and J. Juárez, Jr. 1959. Evaluation of the effects of organic matter and other soil characteristics upon the aggregate stability of some tropical soils. Univ. P.R. J. Agri. 63(4): 268-272.

18. Lugo-López, M.A. and P. Landrau, Jr. 1956. Differential response of some tropical soils to additions of organic matter, Univ. P.R. J. Agri. 40(1): 70-77.

19. Lugo-López, M.A. and P. Landrau, Jr. 1956. Practical evaluation of garbage compost as a fertilizer under conditions in Puerto Rico, Univ. P.R. J. Agri. 40(2): 110-117.

20. Lugo-López, M.A., P. Landrau, Jr., and G. Samuels. 1952. The handling of sugar cane trash II. Effects of various practices on soil properties, Univ. P.R. J. Agri. 36(3): 246-254.

21. Lugo-López, M.A. and L.H. Rivera. 1977. Updated taxonomic classification of the soils of Puerto Rico, Univ. P.R. Agri. Exp. Stn. Bull. 258.

22. Lugo-López, M.A., T.W. Scott, R. Pérez-Escolar, and F. Abruña. 1978. Potencial de los residuos de cosechas en el control de la erosión y como fuente de N en los suelos de los trópicos húmedos. Paper presented at Tropical Soils Fertility Management Workshop, Santo Domingo, Dominican Republic.

23. Lugo-López, M.A., J.M. Wolf, and R. Pérez-Escolar. 1981. Water loss, intake, movement, retention, and availability in major soils of Puerto Rico. Univ. P.R. Agri. Exp. Stn. Bull. 264.

24. Odum, H.T. 1970. Summary: An emerging view of the ecological system at El Verde, Chap. I-10: p. 191-289. *In* H.T. Odum and R.F. Pigeon (ed.) A tropical rain forest: A study of irradiation and ecology at El Verde, Puerto

Rico. U.S. Atomic Energy Commission, National Technical Information Service, Springfield, VA.

25. Pérez-Escolar, R. 1966. Stability of soil aggregates treated with distillery slops or blackstrap molasses, Univ. P.R. J. Agri. 50(3): 174-185.

26. Pérez-Escolar, R. 1966. Reclamation of a saline-sodic soil by use of molasses and distillery slops, Univ. P.R. J. Agri. 50(3): 209-217.

27. Pérez-Escolar, R. 1967. Use of molasses and distillery slops with sulfur for the reclamation of a saline-sodic and a sodic soil from Puerto Rico, Univ. P.R. J. Agri. 51(1): 55-65.

28. Pérez-Escolar, R. 1967. Separation and characterization of the active soil-aggregating agent present in distillery slops, Univ. P.R. J. Agri. 51(4): 304-308.

29. Pérez-Escolar, R. and M.A. Lugo-López. 1968. Nature of aggregation in two tropical soils of Puerto Rico, Univ. P.R. J. Agri. 52(3): 227-232.

30. Pérez-Escolar, R., T.W. Scott, and M.A. Lugo-López. 1978. Legume and non-legume crop residues as sources of N in Oxisols and Ultisols, Univ. P.R. J. Agri. 62(4): 361-366.

31. Samuels, G., M.A. Lugo-López, and P. Landrau, Jr. 1952. The influence of the handling of sugar cane trash on yields and soil properties, Soil Sci. 74(3): 207-215.

32. Sánchez-Irizarry, M.J. 1989. Estudio comparativo de algunas propiedades químicas y físicas de suelos de bosques bajo uso natural y plantaciones silvestres. M.S. Thesis, Univ. P.R. at Mayagüez.

33. Smith, R.M. and F. Abruña. 1955. Soil and water conservation research in Puerto Rico, 1938 to 1947, Univ. P.R. Agri. Exp. Stn. Bull. 124.

34. Smith, R.M. and C.F. Cernuda. 1952. Some characteristics of the macro-structure of some tropical soils in Puerto Rico, Soil Sci. 73(3): 182-193.

35. Smith, R. M., G. Samuels, and C.F. Cernuda. 1951. Organic matter and nitrogen build-ups in some Puerto Rican soil profiles, Soil Sci. 72(6): 409-427.

36. Soil Conservation Service. 1967. Soil survey laboratory data and descriptions for some soils of Puerto Rico and the Virgin Islands. Soil Survey Invest. Report No. 12.

37. Talleyrand, H., R. Pérez-Escolar, M.A. Lugo-López, and T.W. Scott. 1977. Utilization of N from crop residues in Oxisols and Ultisols, Univ. P.R. J. Agri. 61(4): 450-455.

38. Vicente-Chandler, J., 1953. Mulches: An important item in tropical agriculture, J. Soil and Water Conserv. 8(3): 136-140.

39. Vicente-Chandler, J., E. Boneta, F. Abruña, and J. Figarella. 1969. Effects of clean and strip cultivation, and of mulching with grass, coffee pulp, and black plastic, on yields of intensively managed coffee in Puerto Rico, Univ. P.R. J. Agri. 53(2): 124-131.

40. Wahab, A.H. and M.A. Lugo-López. 1981. Mineralization of organic phosphorus in an Ultisol, Univ. P.R. J. Agri. 65(3): 195-204.

Organic Carbon Content of the Soils of Puerto Rico

F.H. Beinroth, P.J. Hernández, A.M. Esnard, G. Acevedo, and B.C. Dubee

Methodology

The calculation of the organic carbon contained in the soils of Puerto Rico to a depth of 1 m required the following data for each soil series mapped on the island: area, thickness of the horizons to 1 m depth, and, for each horizon, bulk density and organic carbon content.

The modern soil survey of Puerto Rico at a scale of 1:20,000 has recently been completed for the entire island and published in six soil survey reports for the following areas: Lajas Valley (1965), Mayagüez (1975), Humacao (1977), San Juan (1978), Ponce (1979), and Arecibo (1982). These reports provided the acreages for each of the 165 soil series mapped on the island. In the case of complexes, such as the Soller-Limestone Rockland Complex, the estimated area of the soil component was used.

The total soil area of Puerto Rico, including the outlying islands like Mona Island off the west coast and Vieques and Culebra off the east coast, amounts to 754,734 ha or 7,545 km^2 (1,864,960 acres or 2,913 square miles). This soil area is about 15 percent less than the total area of Puerto Rico; the difference is accounted for by urban and other built-up areas, surface water, miscellaneous land types such as tidal flats and rockland, and classified military installations that were not mapped.

Horizon thickness was obtained from the profile description of the analyzed pedon or that of the typifying soil series. Laboratory characterization data were available for 91 of the 165 soil series. For the remaining 74 series, the bulk density and organic carbon percentage were estimated from the values determined for the taxonomically most similar pedon analyzed. The SCS soil series/phases interpretation sheets (SOILS-5) were also consulted. In the instances where more than one pedon was analyzed for the same series, mean values were used.

The morphological and analytical information for each of the 165 series was entered in a spreadsheet computer program (Quattro®

Pro v2.0). The appendix contains a sample sheet of the database for five series.

SUMMARY DATA

The soils of Puerto Rico contain a total of about 81 million tons (80,931 x 10^6 kg) of organic carbon.[1] Figure 1 and the tabulation below show how much the nine soil orders recognized in Puerto Rico contribute to the total amount.

Soil Order	Organic Carbon kg m^{-1} x 10^6	Percent of Total C in Puerto Rico Soils	Percent of Total P.R. Soil Area
Ultisols	22,751.3	28.1	24.8
Inceptisols	20,676.6	25.5	36.7
Mollisols	12,605.4	15.6	16.7
Oxisols	10,609.8	13.1	7.9
Histosols	5,179.8	6.4	0.4
Entisols	3,846.0	4.8	5.5
Alfisols	2,833.4	3.5	5.0
Vertisols	2,296.6	2.8	2.8
Spodosols	132.3	0.2	0.2
TOTAL	80,931.2	100.0	100.0

[1] In the interest of keeping this report short, the database has not been included. However, complete data for all of the 165 soil series are available upon request, either as a printout or on diskette. Please direct requests for the database to:

Dr. F.H. Beinroth
Dept. of Agronomy and Soils
UPR Mayagüez Campus
P.O. Box 5000
Mayagüez, PR 00681-5000, USA

Phone: (809) 833-2865; FAX: (809) 265-0220.

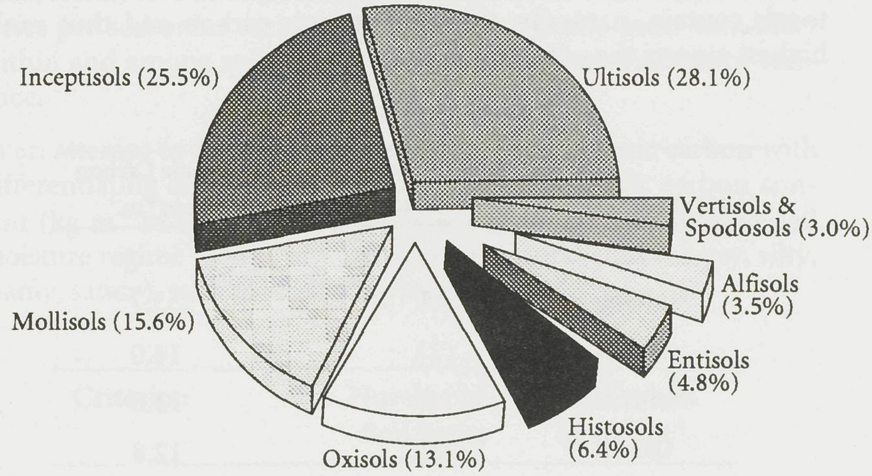


FIGURE 1. Distribution of Soil Organic Carbon in Puerto Rico by Soil Orders

The quantity of organic carbon sequestered by a given soil order is, of course, a direct function of the extent of the soil series belonging to that order. The figures above become, therefore, more meaningful if related to the distribution of soil orders, which is graphically shown in Figure 2.

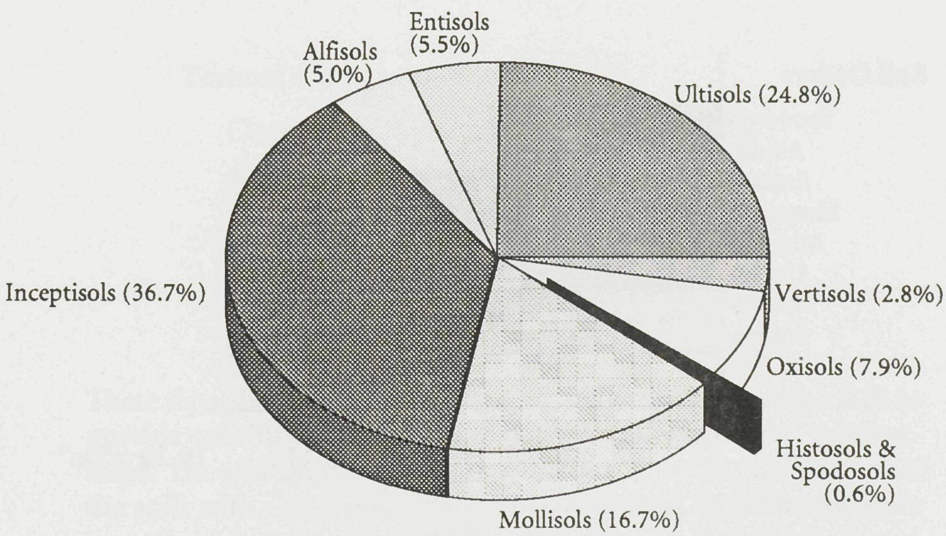


FIGURE 2. Distribution of Soil Orders in Puerto Rico

The island-wide average carbon content of 1 m^2 of soil to 1 m depth is 10.72 kg. If stratified taxonomically per unit area, the Histosols contain, naturally, the most organic carbon and thus rank highest among the nine soil orders:

Soil Order	Number of Soil Series	Organic Carbon $kg\ m^{-2}\ m^{-1}$
Histosols	4	153.7
Oxisols	11	14.0
Vertisols	9	13.0
Ultisols	35	12.8
Mollisols	25	12.5
Inceptisols	41	12.2
Entisols	22	10.0
Alfisols	15	7.3
Spodosols	3	6.5

Figure 3 graphically presents the data in the table above pertaining to the mineral soils (i.e., excluding the Histosols).

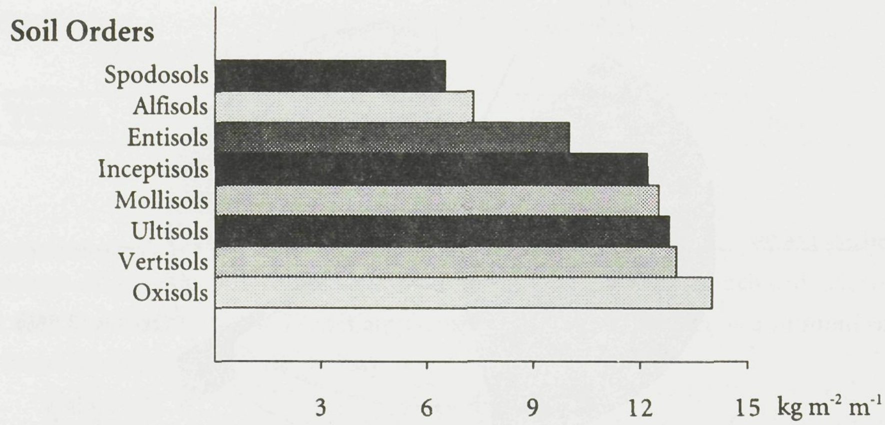


Figure 3. Mean Organic Carbon Contents of Mineral Soils in Puerto Rico

Although carbon levels follow a discernible trend in the mineral soils, it may not be statistically significant since the number of soil series per soil order varies widely and there is also great variability within and among soil series, resulting in high coefficients of variance.

In an attempt to further correlate levels of soil organic carbon with differentiating criteria of Soil Taxonomy, the organic carbon content (kg m^{-2} m^{-1}) of each soil series was grouped according to soil moisture regime (aquic, udic, ustic) and textural class (clayey, silty, loamy, sandy), with the following results:

Criterion	Number of Soil Series	Org. Carbon kg m^{-2} m^{-1}
Soil Moisture Regime		
Aquic		
Histosols	4	153.7
Other soils	27	17.1
Ustic	38	10.7
Udic	96	10.5
Textural Class		
Clayey	106	12.8
Silty	2	12.0
Loamy	39	9.3
Sandy	14	9.2

These data show that the grouping by soil moisture regimes fails to provide conclusive indications of possible cause and effect relationships. The stratification by textural classes, however, indicates that the soils with clayey and silty texture contained significantly more organic carbon that those with coarser texture. This finding confirms the general notion that, other conditions being equal, clayey soils contain more organic carbon than those with coarser textures.

One obvious reason, then, for the significant amounts of organic carbon sequestered in Puerto Rico's soils is that most of the island's soils are clayey and deep. What specifically accounts for and controls the high levels of organic matter in the soils of Puerto Rico cannot be ascertained on the basis of the data and analyses of this preliminary study. It is presumed, however, that comprehensive analyses of the various combinations of soil parent material and parent rock, the resulting soil mineralogy and particle size distribution, the soil moisture and temperature regime, and taxonomic categories below the order level will reveal some consistent trends. Cluster analysis and other statistical techniques such as regression analysis may facilitate the quantitative substantiation of the trends.

Finally, it must be noted that the accuracy of the calculated quantity of organic carbon sequestered in the soils of Puerto Rico presented in this report is inevitably less than perfect. Major factors contributing to the lack of precision are (1) errors in the field delineation of soil map units, (2) deviations from the model pedon used to represent a map unit resulting from impurities contained in the map unit and variability of relevant soil parameters within the limits of a soil series, and (3) errors in the estimation of soil properties in the cases were no series-specific data were available.

Notwithstanding these shortcomings, however, the organic carbon figures presented in this report probably constitute the best estimates available for a tropical area. The availability of modern soil surveys and detailed laboratory characterization for 188 pedons provide a database that is, perhaps, unexcelled elsewhere in the tropics. These favorable circumstances should lend substance and credibility to the data presented in this report.

Recommendations for Future Soil Carbon Research in Puerto Rico

F.H. Beinroth, L.H. Liegel, and M.A. Lugo-López

On the basis of the information presented in the preceding chapters of this report and considering some relevant research imperatives stipulated in Coleman et al. (1989), we recommend that further research on organic soil carbon be conducted in Puerto Rico to: (a) compile a more comprehensive database, (b) study basic cause and effect relationships, and (c) evaluate organic carbon dynamics in the context of tropical agricultural and forestry ecosystems. In particular, we recommend that efforts be initiated to:

1. expand the data base to include additional parameters that are, or may be, related to organic carbon, such as particle size distribution and water retention difference (WRD), to study cause and effect relationships;

2. georeference all pedons that have analytical characterization data by determining their longitude, latitude, and altitude to facilitate their use in geographic information systems;

3. evaluate relationships between soil organic carbon and particle size distribution, clay mineralogy, sesquioxide content, parent material and parent rock, fabric-related properties, soil temperature and moisture regimes, taxonomic classes, and various combinations of these parameters to determine consistent correlations;

4. evaluate the contribution by fungi and other rhizosphere organisms to total soil carbon and explore the use of microbial carbon as a convenient parameter to monitor trends in organic carbon dynamics and to assess long-term stability of soil organic matter under aerobic conditions in the tropics;

5. identify the parameters that govern lability and stability of carbon in tropical soils and determine which carbon fractions are susceptible to management;

6. determine if native leguminous trees are significant contributors to soil carbon accumulation via successional regrowth after agricultural land is abandoned;
7. make base-line and, subsequently, periodic measurements of soil carbon to study differences between forest plantations, native forest successional types, and nearby agricultural land having soils of similar taxonomy and geomorphology, and relate measured carbon pools to past and present land use systems;
8. evaluate and correlate litter mulches from native and plantation forests with carbon retention in micro- and macroaggregates across different soils and landscapes;
9. monitor soil organic carbon levels in primary and secondary forests, pastures, and cropped fields to determine how land use, climate, kind of soil, and landscape position interact to affect carbon dynamics and relate the findings to (1) soil taxonomic units and other environmental factors, and (2) where possible, to baseline measurements made in 1987;
10. develop alternatives to conventional tillage practices and other traditional soil management technologies, including crop residue incorporation and mulching, for crops, forages, and fruit and forest trees which will contribute to reducing oxidative loss of soil carbon and restoring and sequestering organic matter in tropical soils;
11. establish a permanent benchmark site in the El Yunque tropical rainforest to continually monitor soil moisture, air and soil temperature, bulk density, and organic carbon—with automated data collection equipment, to the extent possible; and
12. develop systems-based computer models that simulate carbon dynamics and fluxes, allowing more accurate assessment of the long-term consequences of land use and management practices relative to carbon dioxide levels in the atmosphere.

An expanded and georeferenced database will allow researchers to conduct the statistical analyses, detect the cause and effect relationships, and establish the correlations that will help elucidate the dynamics of soil carbon dynamics in the tropical soils. This, in turn, will facilitate the identification of the critical controlling factors and the formulation of research imperatives.

In view of the great variability of the island's natural environment, Puerto Rico is a particularly appropriate place to conduct the recommended studies. The climate ranges from semi-arid to perhumid, the geologic make-up provides plutonic, volcanic, metamorphic, and sedimentary rocks, and geomorphic surfaces date from Recent to mid-Miocene (0 to 20 million years). These factors account for the island's pedologic diversity and, with the notable exception of Andisols and Aridisols, equivalents for most of the dominant soils of the tropics can be found in Puerto Rico. The principles developed through research in Puerto Rico would thus be valid for and applicable in many regions elsewhere in the tropics. The availability of a solid and comprehensive soil database and other environmental, agricultural, and forestry data further enhances the island's potential as a place to carry out the recommended studies.

The establishment of a permanent research and monitoring site in the El Yunque rainforest would seem to be a meritorious proposition as it would create a high-rainfall counterpart to the Biosphere Research Area operated by the USDA Soil Conservation Service in a dry environment on St. John in the U.S. Virgin Islands.

Retrospective studies can be used to determine if soil carbon contents measured across the island today can be correlated with past and present major agricultural crops, e.g., coffee, tobacco, sugar cane, and also minor crops. Useful for this work are more than 50 years of records at local agricultural experiment stations and the research experiences of both retired and actively employed scientists of the USDA Agricultural Research Service and the University of Puerto Rico Agricultural Experiment Station network. Trends can be searched for croplands actively cultivated for $\geq$40, 25-39, 15-24, 6-14, and $\leq$5 years, or for former agricultural lands that have been abandoned for similar time periods. The objective would be to determine if certain crop systems deplete organic matter faster than others or encourage its accumulation through successional processes after land is abandoned. Results will be useful in planning sustainable agricultural and forest management systems that sequester rather than deplete soil organic carbon over time. Knowledge gained from such work could also be used to mimic natural succession by planting select tree and shrub species on severely degraded lands found throughout the dry, moist, and wet tropics.

New field studies can help quantify the contribution of roots in fields, grasslands, and different forest types to soil organic carbon accumulation rates. Lugo and Liegel (1987) found that natural forests had greater root biomass but less litter accumulation than did plantation forests. Where local soils are deep and/or favor weathering processes that produce high-clay content, original primary forest growth may have built up large surface and subsurface carbon reserves that Island-wide deforestation, farming, and erosion activities did not deplete in the 1800's and early 1900's. If this is so, then resiliency of lowland tropical soils in the Amazon Basin and elsewhere may be greater than anticipated. This would give greater credence to the belief held by some that tropical soils are sinks rather than sources of carbon in the global carbon cycle.

The role of melanins in carbon storage is a relatively new area of investigation. Original experiments were noteworthy because significant nitrogen fixation occurred under aerobic conditions after addition of "sugarcane culture" (an extract from decomposing sugarcane litter obtained in Barbados) to wheat straw. Adding the culture to straw in laboratory incubation studies also increased initial weight loss by two-fold (Hill and Patriquin 1990). Sugarcane was planted throughout Puerto Rico after Spanish colonization and is still planted across the tropics today in areas where soil carbon remains high under intensive cultivation. Investigating the coupling of metabolism by nitrogen fixers and decomposers in sugarcane and other litter could provide new information about rhizosphere processes of humus, soil structure, and soil carbon formation.

Of particular interest in estimating soil carbon accumulation in secondary forests of Puerto Rico are: (a) why abandoned coffee shade plots in moist life zones had greater organic matter, 9.66 kg m^{-2}, than young and older secondary forests, 8.50 and 9.34 kg m^{-2}, respectively; and (b) why sandy soils derived from granite in wet life zones had greater organic matter, 9.95 kg m^{-2}, than did deep and shallow volcanic clay soils, 6.72 and 6.52 kg m^{-2}, respectively. Generally, organic matter contents are higher with increasing rainfall and clay content. Also of interest is whether new forest inventory data (Birdsey and Weaver 1983) can reveal if native leguminous grasses and trees are significant contributors to soil carbon accumulation, via successional regrowth, after agricultural land is abandoned (Smith et al. 1951).

Making new base-line and periodic measurements of soil carbon across landscapes and vegetation types will help quantify how land use affects total carbon and accumulation rates. Such data are essential for determining which management strategies can be aggressively used to purposely create terrestrial carbon sinks to offset carbon emissions to the atmosphere from fossil fuels (Johnson and Kern 1991). Lugo et al. (1986) already did some comparative work on the Island and have made similar, though more limited, comparisons in Costa Rica and Venezuela (Lugo and Brown 1991).

Finally, additional quantification is needed about the benefits of litter mulch from plantations and natural forests in reducing soil temperatures, increasing soil moisture, promoting fast organic matter turnover because of "priming" properties of certain litter types, and fostering micro- rather than macroaggregates. Lugo and Liegel (1987) found nutrient cycling efficiency and litter accumulation differences between plantations and native forests. Many plantations have been measured twice for yield and soil nutrient status (Liegel 1984, 1991). Monitoring carbon accumulation in select forest and agricultural plots would help determine how land use, climate, soil type, landscape position, and life zone interact to affect major soil carbon sequestration processes.

Literature Cited

Birdsey, R.A. and P.L. Weaver. 1983. Puerto Rico's timberland. Journal of Forestry 81:671-672, 699.

Coleman, D.C., J.M. Oades, and G. Uehara (ed.). 1989. Dynamics of soil organic matter in tropical ecosystems. U. of Hawaii Press, Honolulu.

Hill, N.M., and D.G. Patriquin. 1990. Evidence for the involvement of *Azospirillum brasilense* and *Helicomyces roseus* in the aerobic nitrogen-fixing/cellulolytic system from sugarcane litter. Soil Biology and Biochemistry 22:313-319.

Johnson, M.G., and J.S. Kern. 1991. Sequestering carbon in soils: A workshop to explore the potential for mitigating global climate change. U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR. EPA/600/3-91-031.

Liegel, L.H. 1984. Status, growth, and development of unthinned Honduras pine plantations in Puerto Rico. Turrialba 34:313-324.

Liegel, L.H. (Compiler). 1991. Growth and site relationships of *Pinus caribaea* across the Caribbean Basin. USDA Forest Service General Technical Report SO-83. Southern Forest Experiment Stn., New Orleans, LA.

Lugo, A.E., M.J. Sanchez, and S. Brown. 1986. Land use and organic carbon content of some subtropical soils. Plant and Soil 96:185-196.

Lugo, A.E. and L.H. Liegel. 1987. Comparisons of plantations and natural forests in Puerto Rico. p. 41-44. *In* A.E. Lugo, J.J. Ewel, S.B. Hecht, P.G. Murphy, C. Padoch, M.C. Schmink, and D. Stone (ed.) People and the tropical forest. U.S. Man and the Biosphere Program and U.S. Government Printing Office, Washington, DC.

Lugo, A.E., and S. Brown. 1991. Management of tropical forest lands for maximum soil carbon storage. p. 75-77. *In* M.G. Johnson and J.S. Kern. Sequestering carbon in soils: A workshop to explore the potential for mitigating global climate change. U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR. EPA/600/3-91-031.

Smith, R.M., G. Samuels, and C.F. Cernuda. 1951. Organic matter and nitrogen build-ups in some Puerto Rican soil profiles. Soil Science 72:409-442.

Appendix

Sample sheet of the database (Quattro Pro v2.0)

Thickness cm	Bulk dens. g/cm3	O.C. %	O.C. g/cm3	O.C. Kg/m2	O.C. Kg/series	Area of series m2
Aceitunas	udic	clayey				
18	1.26	1.68	0.381	3.810		
20	1.37	0.78	0.2137	2.137		
20	1.28	0.38	0.0973	0.973		
42	1.28	0.23	0.1236	1.236		
100			0.8157	8.157	376481853.805	46156035
Adjuntas	udic	fine				
13	1.09	3.69	0.5229	5.229		
12	1.14	2.03	0.2777	2.777		
18	1.14	0.8	0.1642	1.642		
18	1.09	0.76	0.1491	1.491		
39	1.05	0.26	0.1065	1.065		
100			1.2203	12.203	107958473.507	8846742
Aguadilla	udic	sandy				
20	1.55	1.94	0.6014	6.014		
31	1.6	0.15	0.0744	0.744		
49	1.55	0.06	0.0456	0.456		
100			0.7214	7.214	82998098.208	11505621
Aguilita	ustic	fine-loamy				
20	1.32	3.13	0.8263	8.263		
13	1.31	1.87	0.3185	3.185		
33			1.1448	11.448	1954779465.462	113975661
Aguirre	ustic	very-fine				
23	1.3	1.76	0.5262	5.262		
23	1.3	0.68	0.2033	2.033		
23	1.3	0.44	0.1316	1.316		
20	1.21	0.4	0.0968	0.968		
11	1.21	0.24	0.0319	0.319		
100			0.9899	9.899	269882846.191	27264639

This cover is

recycled paper