Geographic Assessment of Carbon Stored in Amazonian Terrestrial Ecosystems and Their Soils in Particular

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Geographic Assessment of Carbon Stored in Amazonian Terrestrial Ecosystems and Their Soils in Particular

W.G. Sombroek, P.M. Fearnside and M. Cravo

I. Introduction

The amount of carbon stored in various terrestrial ecosystems is an important factor in the cycling of atmospheric carbon dioxide, one of the greenhouse gases. Assessment of carbon in the aboveground standing biomass has received much attention, but only recently has awareness grown that the carbon pool in soils, in its quantity, its dynamics and its sustainability, is important as well.

Quantitative estimates of soil carbon have relied, by and large, on soil surveys that were carried out for planning of agricultural activities, in which the carbon content played a subordinate role only. Field and laboratory methods of soil characterization need to give more careful attention to the vertical transitions of content and type of roots, organic matter, carbonate carbon and charcoal, and to a much greater depth than the traditional 100 cm. Soil physical properties per horizon, including *in situ* bulk density and soil faunal activity, are required as well.

To better quantify terrestrial carbon pools, it is advocated that new soil mapping be carried out in a more holistic framework, taking natural landscape units as building blocks for digital data bases on landforms, soils, hydrology and vegetation or land use. In this way, small but carbon-significant inclusions in mapping units will be duly accounted for. An early example of such an approach is given for the Paragominas area in the southeast of Pará, Brazil. A contrasting one, for which the field studies are still in progress, deals with the situation in the Middle Madeira River area, south of Manaus, Brazil.

II. Assessment of the Aboveground Biomass and its Carbon Content

The amount of carbon stored in the various terrestrial ecosystems forms an important compartment in the cycle of atmospheric CO_2. Increasing concentration of CO_2 is considered to be a major driving force of worldwide climate change.

The assessment of the amounts and the fluxes of carbon in the standing biomass has received much attention since the 1970s. The storage of carbon in tropical forests, and its release upon deforestation, has prominently figured in international scientific and policy discussions on the hazards of a disastrous anthropogenic climate change (Houghton et al., 1988, 1992; Fearnside, 1996, 1997). The concerns that were raised in fact triggered a major international program — PPG7 — to support Brazil in its efforts to protect its tropical forests. More recently concerns gave rise to an international research program on the Amazon region as a whole: the "Large-Scale Biosphere Atmosphere Experiment in Amazonia" (LBA).

The dwindling acreage of forests worldwide is documented by FAO once per decennium, using remote sensing imagery and country reports. The latest inventory reflects the situation in 1990 (FAO, 1993a). The quantification of carbon stored in the forest's aboveground biomass is less easy. Mostly it is done by using conversion factors for data on timber volume, in m^3 ha^{-1}, of traditional forest inventories, as carried out for commercial purposes (Brown et al., 1989; Alves et al., 1997). These inventories consider only the merchantable trees with a diameter at breast height (DBH) of a minimum size — often 25 cm, but sometimes as small as 10 cm or as large as 50 cm. To arrive at the total aboveground biomass, dry-weight measuring is required at representative sites for calibration purposes. This can be further developed into linear regression models of tree biomass over structural tree parameters (Bruenig et al., 1979, on the MAB/IUFRO studies in San Carlos de Rio Negro). As outlined by Fearnside (1994), the sequence of timber volume measurements and its calibration with dry-weighing of carbon storage is fraught with pitfalls and uncertainties such as the degree of geographic representativeness of the forest inventories and the frequency of nonforest vegetation units or man-induced degradational phases (Sombroek, 1992); the density of the living wood of individual tree species; the volume occupied by palms, creepers, vines and shrubs per ha; the amount of dead wood on the ground; the thickness of the litter layer and the representativeness of the dry-weighing sites (Fearnside, 1994). On the latter, for instance, it is noteworthy that most sites for the Amazon are located in easily accessible parts, such as north of Manaus or in Rondônia. There is not a single weighing result for the vast area of dense but low forest on the Pleistocene "Iça" formation in the central-southern part of Amazonas State with its soils of plinthic character (unit Pp of Figure 1).

It is gradually becoming apparent that the early estimates of 360 t ha^{-1} (Woodwell, 1978) of the total aboveground carbon storage of tropical forest lands, as used for modeling of climate change in the framework of the UNEP/WHO International Scientific Panel on Climate Change (IPCC), are too high. The figure should be scaled down, but probably not as much as the 30% suggested by Brown and Lugo (1992). At one extreme, a "back of the envelope" estimate can be produced using average biomass and region-wide (Brazilian Legal Amazon) deforestation rate (e.g., Fearnside, 1985, 1987). At the next level of detail, state-level deforestation rates can be used (the smallest unit for which deforestation information is available throughout the region, as of 1997). These rates can be combined with state-level averages for carbon stocks, based on re-aggregation of the areas and biomass of the forest types within each state. This has been done at the National Institute for Research in Amazonia (INPA), producing estimates (Fearnside, 1990, 1991) based mainly on the forest type area estimates by Braga (1979) and biomass estimates from a variety of point estimates and anecdotal sources. These estimates were subsequently improved by using area estimates (Fearnside and Ferraz, 1995) from a geographic information system (GIS) analysis of the 1:5,000,000-scale vegetation map of the Brazilian Institute for Environment and Renewable Natural Resources (IBAMA) (IBGE, 1988), producing a series of estimates with successively better biomass information (Fearnside, 1992, 1997).

The success of the strategy of step-by-step improvement of the estimates adopted by the INPA group is in contrast with the results of parallel efforts at the National Institute of Space Research (INPE). There, efforts began in 1990 to digitize the RADAMBRASIL (1978) maps for GIS analysis, together with georeferenced deforestation data. The RADAMBRASIL (1978) maps, produced in the period 1973–1983, with 145 vegetation types in the Legal Amazon, are much more complex than the IBAMA map with 28 types in the same region. In addition, numerous inconsistencies exist among the RADAMBRASIL (1978) volumes in the map code adopted (see Fearnside, 1994).

An analysis at the level of RADAMBRASIL (1978) mapping units within each state is the logical next step in improving the level of detail of aboveground biomass assessment, combining the newly available information on vegetation/land use, geology and geomorphology, hydrology and soils.
It may be noted that recent measurements in Rondônia at the ABRACOS project (Grace et al., 1996) and north of Manaus at the BIONTE project (I. Biot and N. Higuchi, personal communications) have shown that the standing forest may at present be actively sequestering carbon, which would constitute

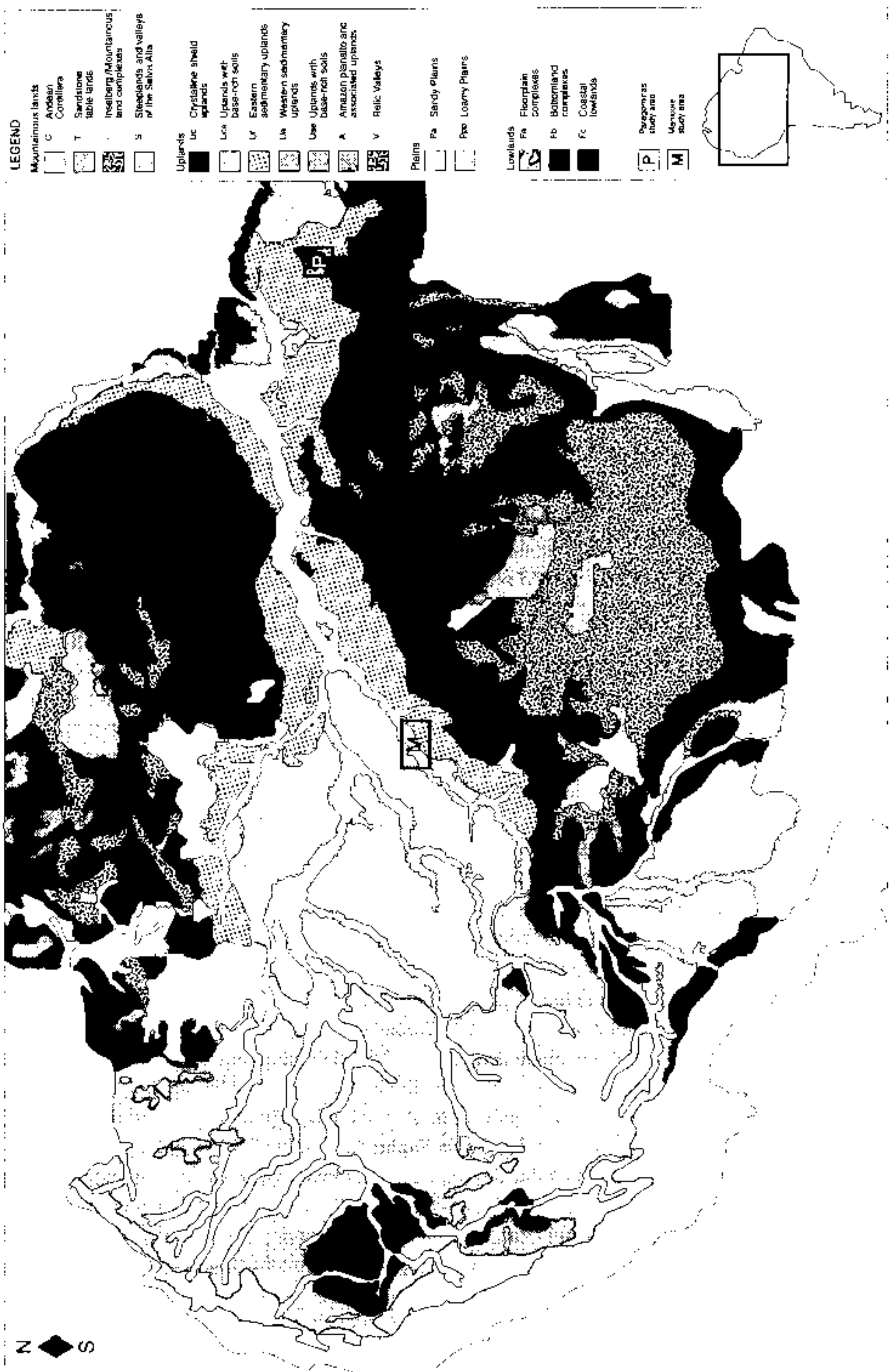

Figure 1. Main landforms of the Amazon region. (Adapted from ISRIC, July 1998.)

proof that the so-called CO_2-fertilization process in agricultural crops is also active in natural woody vegetation.

III. Assessment of Soil Carbon Content

In determining the total potential for CO_2 flux into the atmosphere from large-scale deforestation, one should also look at the below-ground carbon pools. The amount of carbon stored in the living soil (i.e., those surface layers of the land into which roots, microbes and soil animals can penetrate) is very considerable (Delaney et al., 1997) For many temperate ecosystems, the amount is double or triple the amount stored in the aboveground natural or agricultural biomass, and a good part of it is an active component of the carbon cycle. Even the soils under tropical forest contain approximately the same amount of carbon as the lush vegetation above it. The amounts of carbon per main soil type — to 100 cm depth only — are summarized separately by Eswaran et al. (1993) and Sombroek et al. (1993). Klamt and Sombroek (1988) compared the forty-odd Ferralsol (Oxisol) profiles belonging to the collection of ISRIC and originating in all parts of the tropics and subtropics. They arrived at values of 0.64 to 10.19 g per 100 g soil (mean 2.73) for the surface horizons, and 0.07 to 1.37 (mean 0.48) for the subsurface horizons to 100 cm depth.

Recent quantifications of the soil carbon content for the Brazilian Amazon forests are given by Sombroek (1992), mainly on the basis of data gathered in the early 1960s, and more comprehensively by Moraes et al. (1995) on the basis of the RADAMBRASIL (1978) inventory data of the 1970s. However, there are many methodological flaws and uncertainties in determining the total amount and dynamics of the soil carbon and the part stored in the soil organic matter (SOM) in particular. These problems are of three kinds: the methods of sampling and laboratory analyses, the vertical transitions in the soil profile, and those horizontally across the landscape.

A. Sampling and Analytical Problems of Soil Carbon Assessment

The analytical problems are connected with the fact that traditional soil surveys and associated laboratory analyses of soil samples were carried out for planning or improving agricultural activities, in which carbon content per ha played a subordinate role. The density of roots in the various layers/horizons and the number of insects such as ants and termites is described in a qualitative way only, if at all. Sampling of roots for carbon analysis is almost never done.

Often, topsoils are sampled over a standard depth of 0–20 cm as being the future plow-layer. Forest soils, however, may contain two or three horizons within this distance. For instance, The A_{11} horizon of clayey *Latossolos Amarelos*[1] (Oxisols) under primary forest of the Brazilian Amazon may be only 1 to 3 cm thick; the sandy ones may have a 2 to 3 mm surface layer of loose bleached sand. The depth of detailed soil profile descriptions is normally not more than 100 cm when a pit is dug, or 200 cm when a subsequent auger-hole is made.

In extremely sandy or imperfectly drained soils, certain subsoil layers may contain relatively high amounts of carbon. Sampling of humus-rich layers in the subsoil is not always carefully done, in particular when only auger-hole examinations are made — as was the case by and large for the RADAMBRASIL (1978) mapping.

The assessment of carbon in the laboratory also faces many problems. First of all, all soil particles larger than 2 mm are removed by sieving, and are thus not accounted for, though this fraction may

[1] Brazilian nomenclature of EMBRAPA/CNPS; for the names in Soil Taxonomy, FAO-UNESCO legend and the World Reference Base for Soil Resources, see Table 1 (Beinroth, 1975; Camargo et al., 1986; EMBRAPA/SNLC, 1988; Soil Survey Staff, 1992; FAO, 1998).

contain a substantial amount of dead roots, pieces of charcoal (Saldarriaga et al., 1986), indurated SOM/iron complexes from Ortstein layers in *Podzólicos Hidromórficos*, or pedogenic solid calcium carbonates.

Secondly the method of determination of carbon content in the fine earth differs from laboratory to laboratory: Walkley–Black, Allison, or Tiurin methods. Differences may be up to 40% (Allison, 1965). With the claim that minor amounts cannot be measured with any degree of precision, carbon determinations for the deeper subsoil are often not carried out at all though their sum can be quite significant (see below).

Thirdly no conversion from g per 100 g soil (i.e., the fine earth) to g per m^3 or Mg ha^{-1} takes place. Such conversion is necessary to allow comparison with aboveground biomass carbon, which is always given in t ha^{-1}. The conversion would be easy if the bulk density of each soil layer were available routinely. But bulk-density values are seldom measured, and then often in a less-than-accurate manner. In the case of RADAMBRASIL (1978) soil samples, as studied by Moraes et al. (1995) for their carbon content, only about 8% of all horizons concerned had bulk-density figures. These figures, moreover, are not based on real bulk densities as occurring in the field, but rather on laboratory approximations: disturbed sample material is brought into the laboratory, its coarse fraction is removed by sieving, the fine earth is compacted in a metal cylinder of standard size (100 ml) and then weighed. The resulting data may be considerably different from field reality, especially when stony or dense soil layers are concerned. The correct alternative is to apply a coating of plastic sandwich-wrapping material to natural clods, or to collect the same volume of soil at field sampling, by means of a fixed number of metal cylinder fillings — for instance, the rings used for pF-curve determinations. This is easily done, but rarely practiced, and of course requires soil pits or machine-driven deep core probing rather than screw-auger profile examinations as was the practice in most of the exploratory soil inventories of RADAMBRASIL (1978).

In general, differences in bulk densities of soils within the same ecosystem can be up to 60%, and the ranking of soils by their carbon content in Mg ha^{-1} can therefore be substantially different from that in g per 100 g soil. For tropical soils the bulk density can vary from 0.90 to 1.65 g per cm^3. A number of rules of thumb apply: high-organic-matter topsoils have lower bulk density figures than low-content deeper layers; clayey soils are lower in bulk-density than sandy ones; low-iron *Latossolos* have lower bulk density than high-iron ones; subsoils (B-horizons) of *Latossolos* have lower bulk density than those of *Podzólico Vermelho-Amarelo* (Ultisols or Alfisols); imperfectly and poorly drained soils, such as *Plintossolos* and *Gleisolos* have higher bulk density than well-drained soils of the same overall texture.

The following figures are mostly based on bulk-density figures of disturbed samples, but sometimes calibrated with undisturbed samples of CNPS/EMBRAPA-ISRIC (dos Santos and Kauffman, 1995):

- The peaty soils of permanently submerged lowlands have bulk densities of 0.5 g cm^{-3} or less.
- The very heavy textured *Latossolos Amarelo* (LA) of the forested Amazon planalto ("Belterra clays"), have bulk-density values of only 0.90–1.10 down to 200 cm depth or more.
- The texture-differentiated *Podzólicos Vermelho-Amarelo* (PVA), baixa atividade, usually have bulk densities of 1.30–1.40.
- The iron-poor *Areias Quarzosas* under forest have bulk densities of 1.50–1.55 throughout.
- The *Plintossolos* of medium texture under natural savanna vegetation (*campo cerrado*) have bulk density values of 1.55–1.65 throughout.

After deforestation the bulk density of the topsoil increases, through rainfall impact and cattle trampling with 0.05 to 0.20 g cm^{-3} (Fearnside and Barbosa, 1998; Koutika et al., 1997), and this should be taken into account when trying to quantify soil carbon loss in degraded pasture lands or any gain in the few well-managed pastures (Serrão and Toledo, 1992; Cerri et al., 1996).

B. Vertical Differences in Soil Organic Carbon Content

As early as 1974, studies of organic carbon profiles in a number of representative *Latossolos* from all over Brazil, either under forest or under agriculture, were carried out by EMBRAPA, and some useful pedo-transfer functions were developed (Bennema, 1974).

Most soils have a decreasing amount of organic matter with increasing depth, while soil stability increases. There are notable exceptions also in tropical ecosystems (Sombroek et al., 1993). Tropical Podzols, when in a well-drained position, have a characteristic humus accumulation horizon in the subsoil (B_h horizon), which may be within the top 100 cm or at many meters depth. When in imperfectly or poorly drained positions, this accumulation layer is often cemented with iron or aluminum oxides (B_{hir} horizon, or "Ortstein"), which may be of a very irregular or broken nature. Planossolos or well-developed Plintossolos often have a small organic matter jump in the upper part of their pan-like B-horizon. Even well-drained *Podzólicas Vermelho-Amarelo* may have a degree of humus accumulation in the upper part of their B-horizon.

Noteworthy in the context of total carbon assessment in the soil is the irregular occurrence of SOM in the soils of floodplains or recent terraces where the sedimentary layering has not yet been erased by soil biological homogenization or pedogenic differentiation. Sedimentary layers rich in SOM may date from changes in flood regime, local bankfalls or the presence of buried humus-rich former surface horizons. Such a profile from the Lower Amazon area, used in the study of Sutmöller et al. (1966), shows 157 tons of SOM-carbon per ha, totaled over the various layers to 230 cm depth. On eastern Marajó Island, a similar profile showed 217 tons SOM-carbon per ha to 270 cm. As a consequence, the carbon stock of such floodplain soils gains significance in comparison to that of many terra firma soils. Mention should also be made of the scattered occurrences of Latossolo Roxo (an Oxisol) or Terra Roxa Estruturada (an Alfisol), developed from basic rock, with 50 to 100% higher amounts of soil carbon than the predominant soils. The same holds for the many patches of *Terra Preta* do Índio soils, a kind of Plaggensoil, occurring on and around dwelling sites of the pre-Columbian Amerindians, with approximately double the amount of SOM in comparison with neighboring nonanthropogenically enriched soils (Sombroek, 1966, 1992).

The total depth over which the SOM occurs varies highly. Obviously, shallow soils over hard rock (*Solos litólicos*) have limited depth, although rock fissures may contain significant amounts of SOM from former roots. Well-developed tropical soils in general are deep, often much more than 2 m, especially when the parent material consists of unconsolidated sediments (fluviatile, lacustrine, pyroclastic or aeolic). How deep exactly is partly a matter of conjecture, unless one has the opportunity to study deep, fresh road-cuts for the presence of living roots or active soil fauna, such as termites. Rare deep augerings — say to 400 cm depth — with sampling show that there is still some SOM present at this depth — admittedly in small amounts, but still appreciable when related to the thickness of the horizon involved. A striking example is the fresh-pit study of Nepstad et al. (1994) in the Paragominas area of eastern Amazonia. It shows that even at 8 m depth in the heavy textured *Latossolos Amarelo*, there are still living roots and SOM-carbon, with a degree of dynamics (see also Trumbore et al., 1995). Consequently, a full 60% of the SOM-carbon occurs below 100 cm depth. Such forest-growth related deep soil activity is likely to occur elsewhere too, especially when the soil has a low available-moisture storage capacity, a significant dry season (2 to 4 months with less than 100 mm rainfall each) and an absence of any mineral reserve in the upper few meters. This forces roots and termites to deep layers in search of moisture and micro-nutrients. The Nepstad results demonstrate that for the tropical forest zone, one should add a significant amount of soil carbon stock to the amounts mentioned by Eswaran et al. (1993) or Sombroek et al. (1993) for tropical soils in general, and by Moraes et al. (1995, 1996) for the Amazon soils, since these all refer to 100 cm depth only.

One can construct maplets of the total rootable depth that is required to allow forest to survive and grow in marginal rainfall areas (D. Nepstad, in preparation) and then compare these with the geographic reality for modeling the robustness of forest (re-)growth. The Nepstad data regarding total depth of "living soil" can be extrapolated to the deep and well-drained soils of the Cretaceous/Tertiary sediments of east-central Amazonia (land units A and Uf of Figure 1) (Latossolo Amarelo unit of EMBRAPA; see also Rodrigues, 1996). The well-drained soils of the crystalline basement zones of the Guyana and Brazilian shields, *Latossolos Vermelho-Amarelo* and *Podzólicos Vermelho-Amarelo* (PVA), would have a total rootable depth of 5 and 3 m, respectively, as an educated guess.

The imperfectly drained soils of Central Amazonia, such as the *Podzols Hidromórficos* of the upper Rio Negro area and the large extent of Plintossolos or plinthic PVA soils in the areas between the Rio Madeira and the Juruá, as well as those between the middle Rio Negro and the Rio Solimões, all developed on the Pleistocene silty sediments of the Içа formation (unit Pp of Figure 1), have a stop in the downward development of soil biological activity precisely because of the nature of the soil hydrological dynamics. In the well-developed Plintossolos, roots would not go deeper than 1 m or so, and about 2 m deep in the case of PVA plíntico. This is also the reason for the large extent of low forest formations in the above-mentioned areas, although there is no well-defined dry season, and of natural savannas where a degree of dry season is present (see Landsat image of the Middle Madeira area, Figure 2). The ranking of the different soils of the Brazilian Amazon by carbon content, as given by Moraes et al. (1995), is likely to change considerably when the above-suggested depths of the rootable soil are taken into account.

In conclusion, a new effort to quantify soil carbon stocks in the Brazilian Amazon region, and adjoining parts of Colombia, Peru and Bolivia, is called for. It should rely on real bulk-density data, on the absence or presence of deeper layers of living soil and, of course, should try to correlate these features with carbon data for the above-ground biomass of each major soil type. This brings us to the details of the horizontal pattern of tropical soils.

C. The Horizontal Geography of Tropical Soils

The early notion in temperate zone-originated textbooks, that soils of the humid tropics have very little diversity, is presently fully disproved (see FAO/UNESCO soil map of the world, 1994; FAO, 1993b). However, detailed patterns of the geography of soils under forest vegetation types are little studied, although they are basic to forest biodiversity and carbon storage.

In most soil surveys of the reconnaissance type, the mapping units are characterized in the legend by the pedologic classification of the main soil or soils, without precise information on their percentages or any mention of inclusions. At best, one can guess the relative importance from the sequence of soil names. Mention of "association to...", meaning a recognized geographic pattern, or "complex of...", when no pattern was apparent, makes the geographic relationship of soils less vague, and when it is stated "... with ..." or "... and inclusions of ..." one can make an educated guess of the percentage composition of the soil pattern in the landscape. Fully quantitative estimates of the percentage occurrence of all soil components in any mapping unit in reconnaissance surveys were a utopia in the old days, especially when forest- or bush-growth made access and horizontal overview very difficult. However, with the advance of remote sensing techniques such as aerial photography, radar and satellite imagery, one can delineate landscape units ("land system units" = "*unidades de paisagem*") with a high degree of accuracy and, after carefully planned field checks across the elements (or "facets") of such a landscape, arrive at good percentage estimates of the occurrence of these elements in the landscape unit concerned. Every experienced and ecologically / geomorphologically oriented soil surveyor knows that there is a system in the seemingly chaotic spatial distribution of the soils, that each constituent element of a landscape has not only its own topographic character, but also its own soil, its own microclimate, its own internal hydrology and therefore its own vegetation — or its own type of land use when agriculture is well established. Why then not use this knowledge to put soils information in such a landscape-ecological framework? Soil scientists should no longer be on the defensive by stressing a strictly pedologic focus and associated technical terminology to the exclusion of other elements of the landscape. Their soil geographic information will be much more useful to other disciplines if they make the effort to provide their legends in descrip-

Figure 2. Landsat image of the Middle Madira.

tive terminology (drainage condition, depth, color, texture and texture sequence, mode of transition to subsoil, etc.), with the official pedologic classification only at the end and preferably between brackets. In these days of growing acknowledgment of the importance of soils to the diversity of terrestrial ecosystems, on the hydrological cycle and on the fluxes of most greenhouse gases, soil scientists should come out of their narrow agricultural trenches and join forces, on an equal level, with other disciplines in characterizing and evaluating landscapes in a multi-functional cadre.

The idea of using natural landscapes or "Land Systems" as basic building blocks for mapping of rural space is not new. It was first used in Australia, soon after the Second World War. It was subsequently applied in many English-language countries in Africa, by the British Land Resources Development Centre. The CIAT study on "Lands of Tropical America" has land systems as the starting point (Cochrane and Sanchez, 1982). The concept was also promoted by French geomorphologists such as Tricart (1977), which in turn influenced the recent work of IBGE geographers (viz. the PMACI study on the southwestern Brazilian Amazon region: IBGE, 1990), and of the Geography Department of the University of São Paulo (Ab'Saber, 1996). A generalized map of the main land systems in the whole Amazon region is presented in Figure 3.

IV. Examples of a Landscape-Ecological Approach to Carbon Assessment

The first author of the present article used the land-system approach in the early 1960s, for the reconnaissance soil survey cum forest inventory of the Guamá-Imperatriz area across the then-still-forested part of southeastern Pará (Sombroek, 1962, 1966). The area around the town of Paragominas, for instance, was denominated as the "Candiru" land-unit, with a total area of about 350,000 ha and characteristics as shown in Figure 1[2].

In this land unit, the forest cover was dense and high, with scattered emergents and relatively open undergrowth because of the near-absence of creepers and climbers. As reported by Glerum and Smit (1962), there was a high number of trees per hectare (124) and a substantially higher gross timber volume (191.6 m^3 ha^{-1}) than in the land units immediately north or south (Médio Guamá: 108 trees ha^{-1}, and 161.2 m^3 ha^{-1}; Alto Guamá: 94 trees ha^{-1} and 121.1 m^3 ha^{-1}). One tree species, Pau amarelo (*Euxilophora paraensis*) was strongly concentrated on the concretionary soils of the edges of the low-plateau and on its scarps (see also Appendix 3 of Sombroek, 1966 for a detailed sample area around 130 km south of Guamá). The central parts of the plateau (element *a*), had scattered Angelim pedra (*Hymenolobium excelsum*) as emergent while Pau roxo (*Peltogyne lecointei*) and Quaruba (*Vochysia maxima*) tended to be most frequent on the middle-terrace land. The latter facet had also a unique and exquisite fragrance, due to the presence of a "Vanilla" orchid.

Because of the high quality of the forest on this land unit, and at the specific request of the SPVEA — the regional development organization to which the FAO/UNESCO inventory team was attached — a good part of the land unit was recommended for sustainable timber production, to be protected by a buffer zone of controlled small-holder agricultural settlements that would also provide forestry labor. It is very disheartening to observe after 35 years that this early effort of ecologic-economic zoning in a tropical forest area failed miserably. Immediately after the technical survey data became available, they were used by unscrupulous individuals in a predatory way: indiscriminate clear-cutting of all valuable timber, followed by large-scale burning and establishment of extensive cattle ranches on most parts of which the soils soon became degraded because of lack of maintenance of the grass cover (Nepstad et al., 1991; Trumbore et al.October 13, 1999, 1995).

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[2] Estimates on total rootable depth from unpublished field observations on the many fresh road-cuts in 1961; estimates on total SOM-carbon storage based on unpublished profile descriptions and analytical data of the EMBRAPA/CNPS central soil laboratory in Rio de Janeiro. For location of the Paragominas area, see site P of Figure 1.

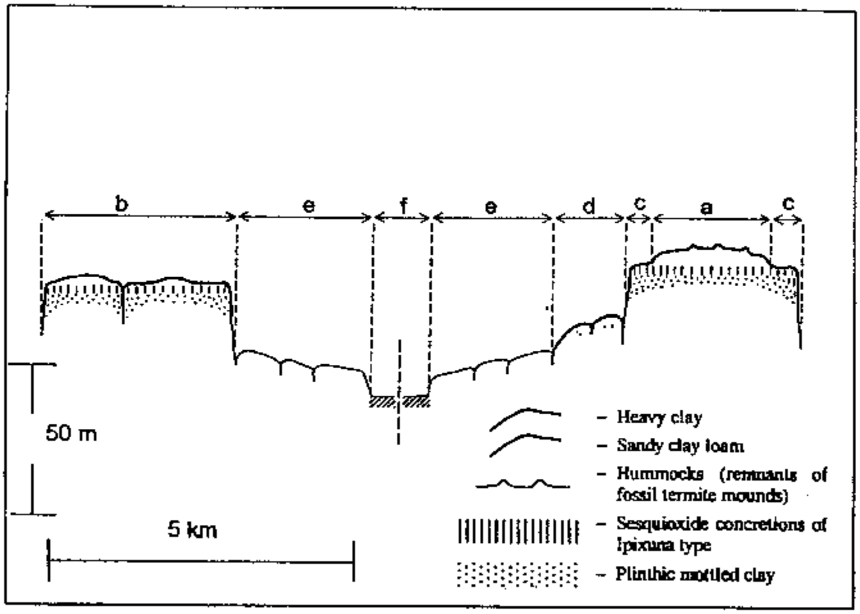

Figure 3. Sketch of the structure of the "Cardirú" land-unit in the Paragominas area of Pará, Brazil.

The above-described early example of a landscape-ecological approach was never applied in neighboring areas or even referred to in subsequent studies in the area itself. However, even in the present-day deforested situation, the basic physical elements of the local landscape remain intact, and their pattern forms a good starting point for the assessment and spatial differentiation of degradation features.

The multi-disciplinary physico-biotic database of landscape-system units can these days be harnessed, and manipulated for modeling purposes, much more easily than before because of the development of digital data storage systems and geographic information systems. An appropriate vehicle for geographic studies that contain a substantial soil element would be the SOTER system (Soil and Terrain Digital Data Base), developed by a working group of the International Society of Soil Science (ISSS). It was subsequently adopted by FAO and UNEP as an appropriate data storage and processing system, with an inbuilt capacity to be combined with relational databases on climate, hydrological resources, natural land cover or land-use and settlement patterns (UNEP/ISSS/ISRIC/-FAO, 1993).

The first Latin American application of the SOTER approach was through a joint project by national soil institutions of Brazil, Uruguay and Argentina in their frontier areas. Many more areas are now being covered with the same or a comparable approach. A number of software packages for practical uses of the database system have been developed, such as on erosion hazards or production capacity (FAO/UNEP/ISRIC, 1998). A similar package can be developed for geographic quantification of the SOM-carbon per landscape element or for the land-unit as a whole.

It may be mentioned that the Ecologic-Economic Zoning Program (*Zoneamento Ecológico-Econômico*), now starting in some Amazon priority areas of Integrated Environmental Management, takes the natural landscape units as a starting point for the physico-biotic part of its diagnostics. The soils element thereof will be taken care of by EMBRAPA specialists, this time cooperating very closely with geologists, geomorphologists, hydrologists and biologists in assembling the digital database information.

One of the first pilot areas of the zoning program is the Manicoré-Novo Aripuanã area along the Middle Madeira river in the state of Amazonas. Two strikingly different land systems are involved, on the left and right side of the river, respectively (see satellite image, Figure 2). In the center is the recent floodplain of the Madeira river, with its many pointbars "Restingas" and cut-off side lakes (oxbow lakes).

The land unit[3] on the western (left) bank of the river has silty sediments of the mid-Pleistocene Içа formation. Its flat interfluvial areas have a dense, low forest with many palms, or an open savanna vegetation — the blotchy parts — with imperfectly or poorly drained soils, moderately to strongly texture-differentiated and with a plinthic layer between 50 and 150 cm depth (*Plintossolos*; *Planossolos* when having an abrupt transition; Podzols when having a humus accumulation above the plinthite); the rootable depth is 100–150 cm, and the SOM-carbon content is about 60 t ha^{-1} (4 profiles). The sloping parts have a rather low, dense forest, of about 100 m^3 ha^{-1} timber volume (DBH 31.8 cm or more; 34 samples) and moderately well- to imperfectly-drained silty clay soils that easily slake and are mottled reddish at depth (*Podzólicos Vermelho Amarelo, plíntico*); their rootable depth is about 200 cm and the carbon content about 120 t ha^{-1} (6 profiles).

The land unit of the eastern (right) bank of the main river has mid-Pleistocene sandy to loamy sediments, probably derived from the Proterozoic Prainha formation farther to the south. Its flat terrace lands have high forest (about 130 m^3 ha^{-1}; 25 samples) and well-drained, very deep, friable and stable sandy clay loam soils (*Latossolos Amarelo*). The rootable depth is at least 5 m and the total SOM-carbon is the order of 160 t ha^{-1} (3 profiles). The terrace lands are interspersed with lower-level abandoned river-beds – the elongated narrow bands of vague grey – that are filled with white sands (presumably *Podzols hidromórficos* in the actual field observations) and are covered with a shrubby savanna vegetation. The higher river banks, along the present-day rivers and rivulets, are occupied by traditional small-holder farmers and forest-product gatherers (*ribeirinhos*); the mode of settlement is semi-sedentary rather than of shifting-cultivation type because of the nearly continuous presence of *Terra Preta do Índio* on these riverbank stretches (M. Von Roosmalen, personal communication).

V. Conclusion

A variety of strategies exists that might be adopted in estimating the stock of carbon presently contained in Amazonian landscapes and the emission of CO_2 that could be expected when these landscapes are subjected to land-use changes. The information that already exists has to be interpreted in the most effective way, and programs to acquire new information need to be designed, such that the uncertainty regarding carbon stocks and emissions is lowered as efficiently as possible — that is, obtaining the greatest reduction in uncertainty for a given amount of investment.

Existing information can be aggregated in a variety of ways to produce emission estimates. The degree of aggregation that is appropriate depends on the level of detail of the original information. Vegetation mapping units of the RADAMBRASIL (1978) type can be further subdivided on the basis of topography and soil differences to produce land units that make more sense as the basis both for development or conservation planning and for the current purpose of assessing carbon stocks and potential emissions.

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[3] All descriptions and quantitative estimates are provisional, based on comparative analysis of relevant geological, geomorphological, soil and forestry survey data of the Purus volume of RADAMBRASIL (1978), over an area of 60,000 km^2; more detailed sampling and analysis is ongoing for the 9000 km^2 of the area shown in Figure 2.

The gain to be expected from each successive increase in the level of detail of mapping can be estimated from comparing the results of carbon estimates made at different levels of aggregation within a defined study area that is small enough to make mapping at a detailed (i.e., land-units) level practical. The Middle Madeira area, as described above, is suggested for this purpose.

In summary, it would seem to be appropriate to use the landscape-ecological approach and the SOTER vehicle as a means of correlating carbon storage and dynamics in soils with that of the above-ground biomass and ecosystem carbon. Also, the many other functions of "land" in the holistic sense, as the term is used in UNCED's Agenda 21 (FAO, 1995), can best be studied in the landscape-ecological context. As recently stated by Turner et al. (1997), continued database development is required, including close attention to the methodologies used for quantifying carbon content and fluxes in the various compartments of ecosystems, if carbon budget assessments are to be sufficiently reliable for use by the international policy community in proposing climate change controls.

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