Environ Monit Assess (2008) 140:279–289
DOI 10.1007/s10661-007-9866-0

Soil and vegetation carbon stocks in Brazilian Western Amazonia: relationships and ecological implications for natural landscapes

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Received: 8 November 2006 / Accepted: 3 July 2007 / Published online: 11 September 2007

Abstract The relationships between soils attributes, soil carbon stocks and vegetation carbon stocks are poorly know in Amazonia, even at regional scale. In this paper, we used the large and reliable soil database from Western Amazonia obtained from the RADAMBRASIL project and recent estimates of vegetation biomass to investigate some environmental relationships, quantifying C stocks of intact ecosystem in Western Amazonia. The results allowed separating the western Amazonia into 6 sectors, called pedo-zones: Roraima, Rio Negro Basin, Tertiary Plateaux of the Amazon, Javari-Juruá-Purus lowland, Acre Basin and Rondonia uplands. The highest C stock for the whole soil is observed in the Acre and in the Rio Negro sectors. In the former, this is due to the high nutrient status and high clay activity, whereas in the latter, it is attributed to a downward carbon movement attributed to widespread podzolization and arenization, forming spodic horizons. The youthful nature of shallow soils of the Javari-Juruá-Purus lowlands, associated with high Al, results in a high phytomass C/soil C ratio. A similar trend was observed for the shallow soils from the Roraima and Rondonia highlands. A consistent east–west decline in biomass carbon in the Rio Negro Basin sector is associated with increasing rainfall and higher sand amounts. It is related to lesser C protection and greater C loss of sandy soils, subjected to active chemical leaching and widespread podzolization. Also, these soils possess lower cation exchangeable capacity and lower water retention capacity. Zones where deeply weathered Latosols dominate have a overall pattern of high C sequestration, and greater than the shallower soils from the upper Amazon, west of Madeira and Negro rivers. This was attributed to deeper incorporation of carbon in these clayey and highly pedo-bioturbated soils. The results highlight the urgent need for refining soil data at an appropriate scale for C stocks calculations purposes in Amazonia. There is a risk of misinterpreting C stocks in Amazonia when such great pedological variability is not taken into account.

Keywords Aboveground biomass · Soil carbon stocks · Western Amazonia soils

Introduction

The relationship between soil carbon stocks and carbon fixation in natural and anthropic vegetation remains one of the least studied issues in the understanding of the carbon cycle for terrestrial Amazonia. Emphasis has been placed on measurements of carbon fixation by secondary forests (Fearnside and Guimarães 1996) or

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measurements of carbon emissions following land-use changes (Fearnside 2000). Basically, the amount and quality of natural soil organic carbon is highly influenced by vegetation type and land use, as recently demonstrated by Andrade et al. (2004). Most studies on carbon stocks in aboveground vegetation do not consider the inherent soil constraints for allowing various rates of biomass production.

Biomass of intact vegetation, both forest and non-forest types, are important components for quantifying C pools and C dynamics in Amazon ecosystem (Cummings et al. 2002), although reliable information on total above ground biomass is scarce. Most available information is based on forest inventory data (Brown and Lugo 1992; Fearnside 1992; Brasil 2004) at different scales, as well as field measurements of forest trees (e.g.; Higuchi et al. 1994).

Recently, reliable field data based on forest structure was provided by Barbosa and Fearnside (1999) for north-western Amazonia, where a high diversity of vegetation types occur, and for forests of southwestern Amazonia (Cummings et al. 2002). These studies highlighted the wide range of biomass estimates for different vegetation types in western Amazonia.

On the other hand, a recent compilation of vegetation biomass for the entire Amazon region, based on the RADAMBRASIL forest inventory (Brasil 2004), has shown many inconsistencies, possibly due to lack of accuracy for some vegetation types, and overestimation of poorly-known non-forest vegetation.

The objective of the present paper was to model and interpret the available information on soil and biomass carbon stocks and the relationship between both, from a regional viewpoint, taking into account the ecological implications and trends in carbon dynamics in the whole ecosystem of western Amazonia.

Material and methods

Study area

The study area comprises the Western Amazonia region, encompassing the Brazilian states of Amazon, Acre, Rondônia and Roraima (Fig. 1). The soil cover is dominated by Latosols (Oxisols), Spodosols, Argisols (Ultisols) and Cambisols (Inceptsols), forming many different soil associations. Pedological data was based on regional soil surveys, using well-established analytical data for carbon amounts (EMBRAPA 2007; Brasil 1975a, b, c, 1976a, b, c, 1977a, b, c, 1978a, b, c, 1979). The predominant vegetation types are dense and open lowlands and dense submontane ombrophilous forest.

Soil carbon stocks estimates

Soil carbon stocks were obtained from the large database of RADAMBRASIL and EMBRAPA, based on 347 complete soil profiles: 86 pedons from the Acre State (Brasil 1976a, 1977a), 129 pedons from Amazonas (Brasil 1975a, b, 1976a, b, c, 1977a, b, c, 1978a, b, c), 43 pedons from Rondonia (Brasil 1978c, 1979) and 89 pedons from Roraima (Brasil 1975b, c, 1978b). All analytical data were processed using ArcGIS 9.0 software for area calculation and map production. The original soil map had 706 polygons divided in 347 mapping units, according with the number of soil classes in each soil unit. Soils were classified according with the Brazilian System of Soil Classification (EMBRAPA 1999).

In order to simplify the overall calculations, some generalization was necessary and soils were grouped following the recommendations of Houghton et al. (1997), aimed at carbon stocks inventories, taking into account texture, clay activity, base saturation and soil moisture. For this procedure, mapping units were separated into six groups, with the following main components G1, luvisols and eutric argisols and eutric cambisols; G2, cambisols; G3, dystric argisols, aluminic argisols and nitosols; G4, other aluminic soils (formerly alisols); G5, gleysols, fluvic neosols (entisols) and plinthosols and G6, latosols and quartz-arenic neosols.

Soil carbon stocks for each soil horizon (CS_h) were obtained by multiplying the carbon content, soil bulk density and depth of a given horizon (Eq. 1). For each diagnostic A and B horizon the carbon stocks for each soil profile – CS_A (Eq. 2) and CS_B (Eq. 3), respectively – were calculated considering the total volume of each one, including the transitional horizons. The total Carbon Stocks (CS) was based on the sum of the whole profile (Eq. 4).

$$\mathrm{CS}_h = C \times \mathrm{SD} \times h \tag{1}$$

$$\mathrm{CS}_A = \sum \mathrm{CS}_h \tag{2}$$

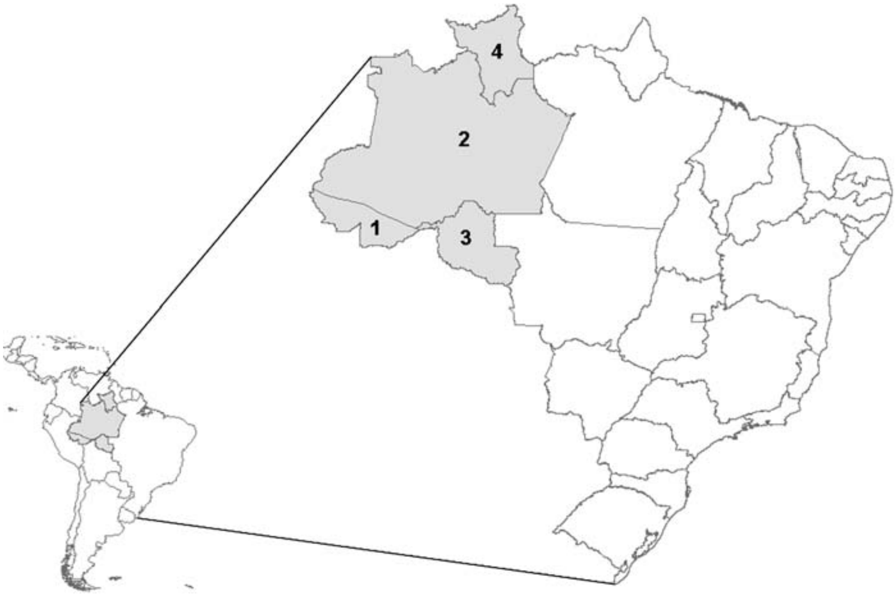


Fig. 1 Western Amazonia and its location in Brazil and South America, with a total area of 2,195,921 km^2 (*1* Acre; *2* Amazonas; *3* Rondonia; *4* Roraima)

$$\mathrm{CS}_B = \sum \mathrm{CS}_h \tag{3}$$

$$\mathrm{CS}_p = \sum_B^A \mathrm{CS}_h \tag{4}$$

where:

CS Soil carbon stocks (kg m^{-2})
C Carbon content [% (weight/weight)]
SD Soil density (g cm^{-3})
h Depth (m)

Whenever soil bulk density was not determined, we estimated their values through multilinear equations relating clay content, carbon content and pH, obtained by representative soil data from the Amazon Basin (Bernoux 1998; Bernoux et al. 1998). For soil horizons with less than 20% clay, we used the following equation:

$$\mathrm{SD} = 0.0181 \times (100 - \mathrm{CC} - 5) - 0.08 \times \mathrm{OC}, r^2 = 0.66 \tag{5}$$

In all remaining cases, the calculations were performed using specific equations for each soil group, as described below:

- G1, G2, G3, G4 groups:

$$\mathrm{SD} = 1.394 - (0.0051 \times \mathrm{CC}) - (0.307 \times \mathrm{OC}), r^2 = 0.47 \tag{6}$$

- G5 group:

$$\mathrm{SD} = 1.58 - (0.0040 \times \mathrm{CC}) - (0.050 \times \mathrm{OC}) - (0.047 \times \mathrm{pH}), r^2 = 0.51 \tag{7}$$

- G6 group:

$$\mathrm{SD} = 1.404 - (0.0040 \times \mathrm{CC}) - (0.048 \times \mathrm{OC}), r^2 = 0.71 \tag{8}$$

where:

CC Clay content following dispersion with Na-hexametaphosphate [% (weight/weight)]

OC Organic carbon by Walkley and Black (1934) [% (weight/weight)]
pH pH in water

Soil carbon maps

For the soil carbon map of Western Amazonia, we used the pondered mean of carbon stocks for each soil mapping unit, in each polygon, using ArcGIS 9.0.

Carbon stocks estimates of the main vegetation type for Western Amazonia

The present calculation outline made use of the vegetation classification adopted by Brazilian Institute of Geography and Statistic (IBGE 1988) for the 1:5,000,000 scale vegetation map. For calculation purposes, we quantified the mean carbon stocks (Mg/ha) for plant biomass (live and dead) for western Amazonia, encompassing the states of Acre, Amazonas, Roraima e Rondonia. Additionally, the official Brazilian Reference Report (Brasil 2004) and data published by Barbosa and Fearnside (1999) were also used for these estimates (Table 1).

Vegetation map

The distribution of the different vegetation types was based on the IBGE (1988) regional vegetation map, georeferenciated for the same cartographical basis.

Table 1 Carbon stocks in biomass for different vegetation types in Western Amazonia used in this work (modified from Barbosa and Fearnside 1999 and Brasil 2004)

Legend	Vegetation type	Carbon stocks (Mg/ha) (Brasil 2004)	Carbon stocks (Mg/ha) (Barbosa and Fearnside 1999)
A	Anthropic area	–	–
Aa	Alluvial open ombrophilous forest	130.72	122.93
Ab	Lowland open ombrophilous forest	107.45	123.34
As	Submontane open ombrophilous forest	104.01	116.70
D	Anthropic area	–	–
Da	Dense alluvial ombrophilous forest	123.15	148.00
Db	Dense lowland ombrophilous forest	122.81	148.50
Dm	Dense montane ombrophilous forest	78.23	125.00
Ds	Dense submontane ombrophilous forest	100.30	140.50
F	Anthropic area	–	–
Fs	Semideciduous submontane forest	152.93	121.50
LO	Areas of ecological tension and contact: woody oligothrophic vegetation of swampy and sandy areas/ombrophilous forest	128.63	133.00
La	Open woody oligothrophic vegetation of swampy and sandy areas	18.03	19.40
Ld	Dense woody oligothrophic vegetation of swampy and sandy areas	134.46	23.80
Lg	Woody grassland oligothrophic vegetation of swampy and sandy areas	125.46	4.75
ON	Areas of ecological tension and contact: ombrophilous forest/ semideciduous forest	137.87	121.50
Pa	Pioneer vegetation	111.31	16.65
S	Anthropic área	–	–
SN	Areas of ecological tension and contact: savanna/semideciduous forest	133.84	85.00
SO	Areas of ecological tension and contact: savanna/ombrophilous forest	118.78	85.00
As	Open woody savanna	15.39	3.00
Sg	Woody grassland savanna	114.76	1.65
Sp	Savanna parkland	107.08	3.00
Td	Dense steppe-like savanna	114.76	14.50
Tp	Steppe-like savanna parkland	107.08	2.80
Rm	Highland ecological refuge	110.85	1.55

According to this map, the vegetation types in Western Amazonia are listed in Table 1.

Calculation of the aboveground carbon stocks

The reference report published by the Brazilian Science and Technology Ministry shows estimates of emissions and sequestration of atmospheric C due to changing land uses. For ecotonal (ecological tension) areas, we have calculated the biomass as mean of the two contacting vegetation types. Biomass for Campinarana and Savana types, not measured in the field, were calculated by interpolation, correcting these values for fitting them within the existing range of tree-density values.

Barbosa and Fearnside (1999) presented (live and dead) aboveground biomass data for Roraima, according to the vegetation map of IBGE. Based on this work, carbon stocks in the vegetation types were calculated using conversion of 50% of C for biomass weight (Brown 1986; Montagnini and Porras 1998). For other western Amazonian forest types (Alluvial Open Forest, Lowland Forest and Semideciduous Submontane Forest) we have considered data published by Cummings et al. (2002) for southwestern Amazonian forest types (Fig. 2).

Due to a high heterogeneity of land use covers in Anthropic (replacement) areas, the biomass carbon stocks for these mapping units were not quantified. We considered that any values assumed for anthropic land uses would be, at best, a reasonable guess. Hence, only natural environments are calculated and mapped in this work, excluding the areas under anthropic influence (mapped as blank polygons) from the total area.

Carbon stocks maps

The maps of carbon stocks at the soil surface, subsurface, total soil and vegetation were overlain with rainfall data (INMET 2007), allowing interpretation of carbon behaviour following the regional climatic gradient, using the software ArcGIS 9.0.

The indexes associating carbon amounts in vegetation with soil carbon stocks (total, surface and subsurface), were obtained by dividing a given amount of carbon in the biomass for the value found at a given soil mapping unit. This was possible since soil and vegetation data were individually plotted, allowing these calculations in a simple and fast way, using Geography Information System. All maps were derived from these basic soil and vegetation carbon and rainfall data.

Fig. 2 Total carbon stocks in vegetation

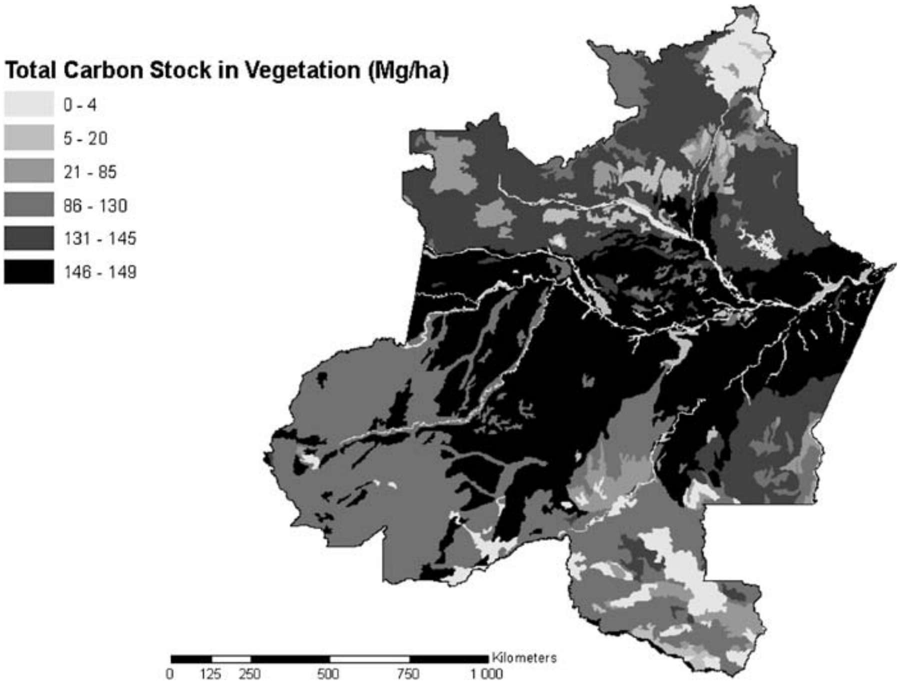
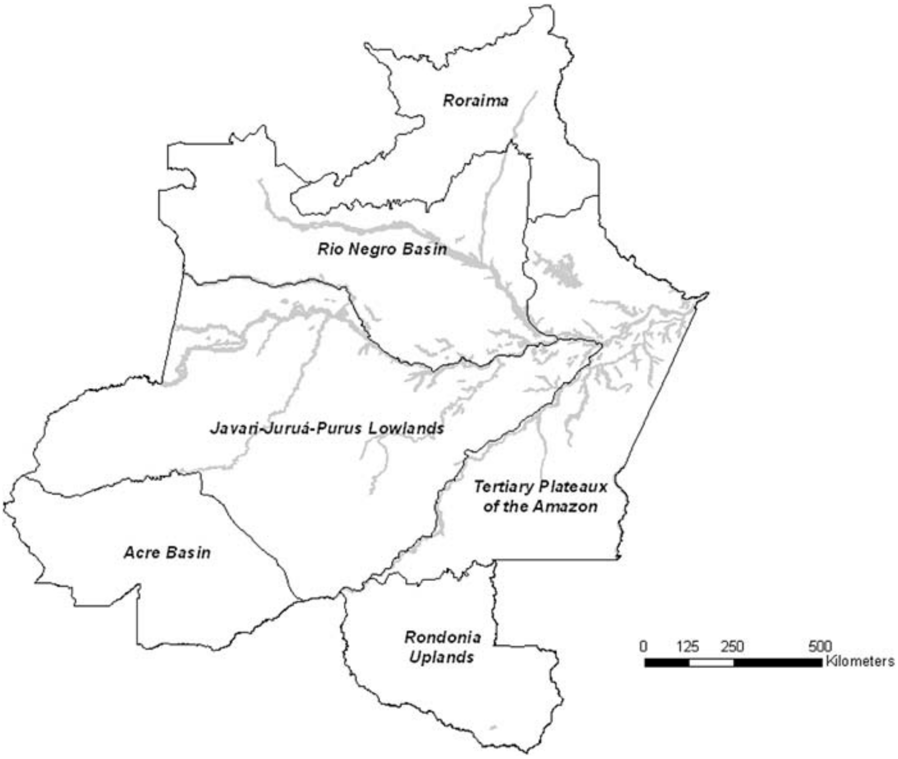


Fig. 3 The environmental sectors (pedo-zones) of Western Amazonia, based on geomorphological and pedological characteristics (see Table 2 for details)



Results

Based on pedological and geomorphological characteristics, western Amazonia was divided into six sectors or pedo-zones (Fig. 3), each one associated with a particular set of soils and landforms, as described in Table 2. These pedo-zones formed the framework for the following discussion of carbon stocks estimates.

Total carbon stocks

The total C stocks in Western Amazonia soils (Fig. 4) reveals an interesting trend of higher total C stock in the Acre and in the Rio Negro basin pedo-zones, for two different reasons; (1) in the Negro basin, most C is being actually lost from the topsoil to the subsurface layers (spodic horizons) by podzolization and

Table 2 Summary of the main characteristics of the environmental sectors of Western Amazonia

Zone or sector	Soils	Landforms and geology	Relative area (%)
Acre basin	Eutric cambisols; luvisols; eutric neosols (2:1 clays)	Gentle and undulating hills, flat alluvial plains; terraces of 2:1 clayey quaternary sediments	10.95
Javari-Juruá-Purus Lowlands	Aluminic plinthosols, dystric gleysols, alisols; dystric and aluminic argisols	Gentle hills, alluvial plains of quartzose, acid quaternary sediments	31.73
Rondonia Uplands	Dystric argisols, latosols, nitosols	Deeply dissected hills and tablelands on tertiary sediments and crystalline rocks	8.64
Roraima	Dystric argisols, yellow latosols, dystric litholic neosols, minor plinthosols and gleysols	Variable: highly dissected to lowland flats and terraces; crystalline rocks with quartzitic high plateaux	11.54
Rio Negro basin	Quartzarenic neosol, hydromorphic spodosols	Extensive waterlogged sandy plains on quaternary sediments	19.54
Tertiary Plateaux of the Amazon	Yellow and red–yellow dystric latosols and argisols	Tablelands and gently dissected hills on tertiary “Barreiras Group” sediments	17.60

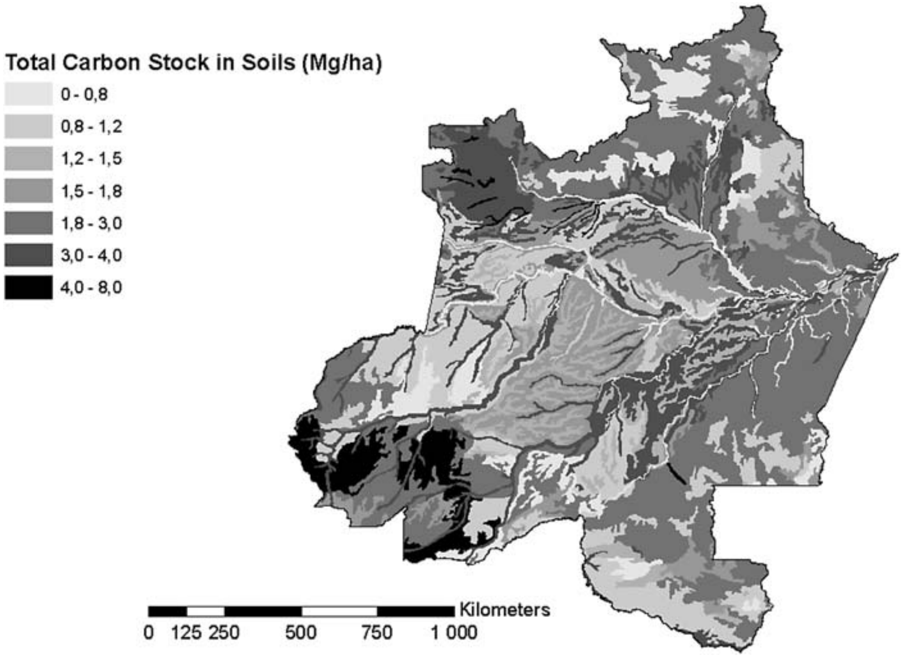


Fig. 4 Total C stocks in Western Amazonia soils

deep arenization, meaning active carbon losses due to low physical carbon protection in these sandy soils. (2) On the other hand, in the Acre sector higher carbon stocks values are influenced by high activity 2:1 clays of Andean origin, with high nutrient status than elsewhere in Amazonia, enhancing primary productivity.

The high C aboveground (shoot) biomass/C soil (Fig. 5) in the Javari-Juruá-Purus lowlands is a clear indication of the recent development of the Aluminic

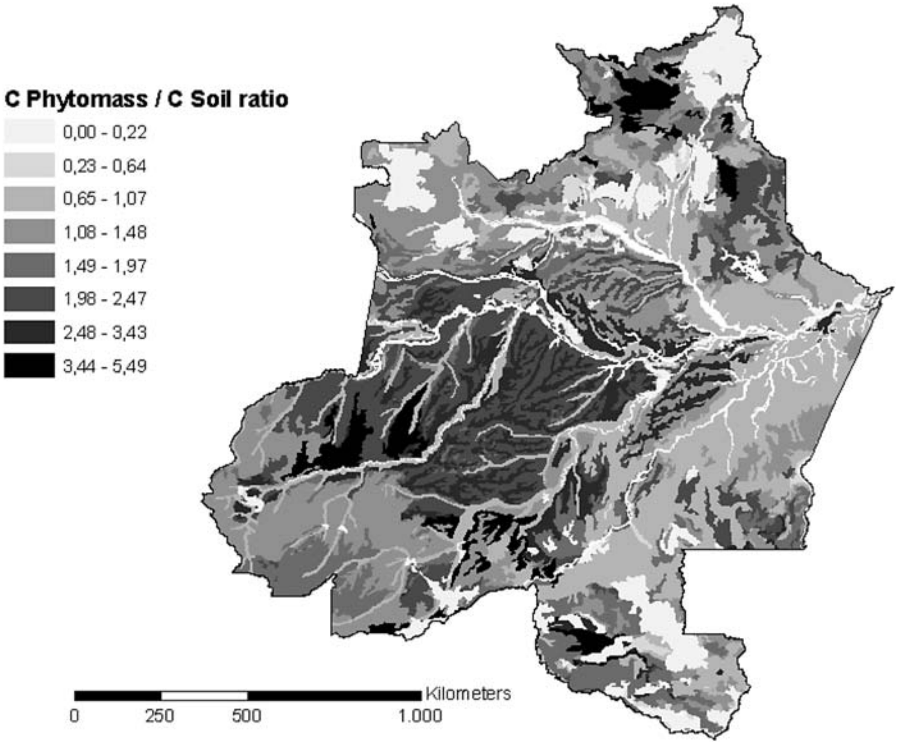
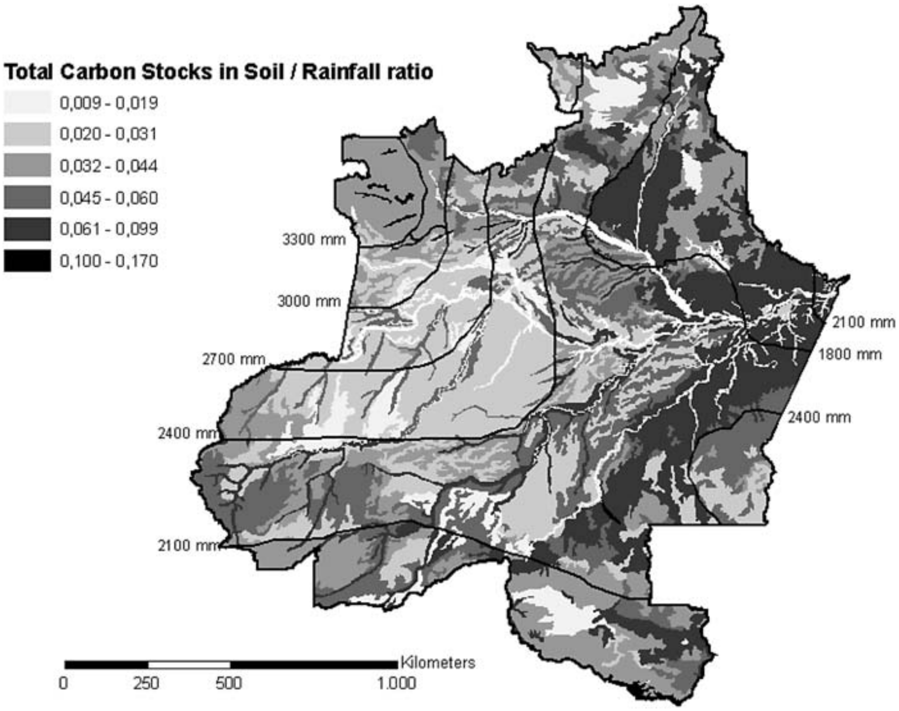


Fig. 5 The C phytomass/C soil in Western Amazonia

Fig. 6 Ratio between total of carbon in soil divided by rainfall in Western Amazonia

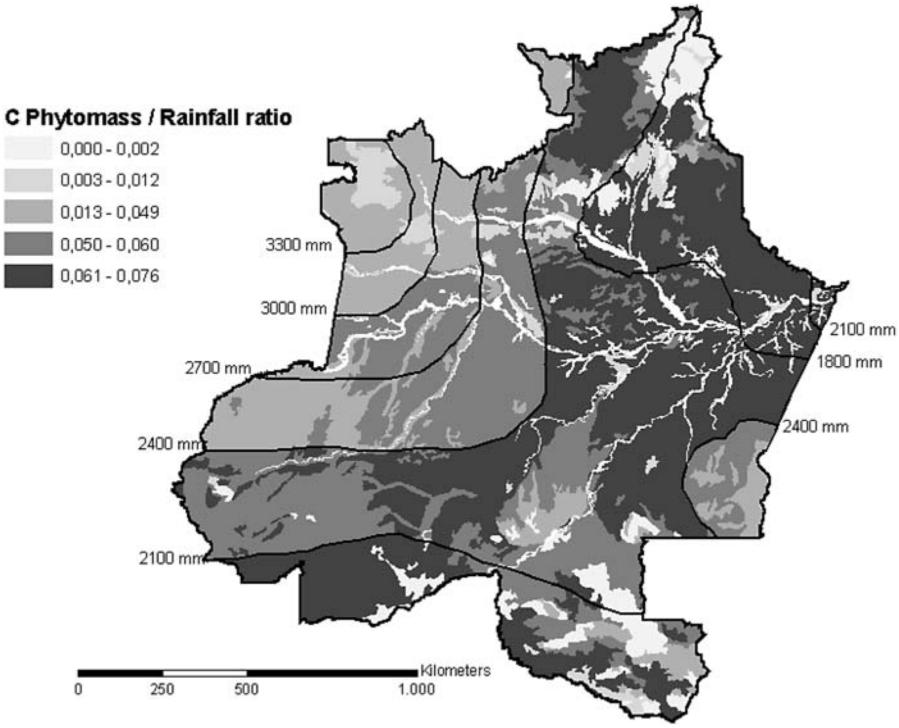


(Al-rich) hydromorphic Plinthosol, under rain forest of primary sucession, in which C has not been fully incorporated. The same trend is observed in the shallower soils of the highlands pedo-zones of Roraima and Rondonia.

Relationship between rainfall and total soil carbon

Figure 6 shows a climatic index of C, expressed as the ratio between total soil carbon and mean rainfall, for

Fig. 7 Ratio between aboveground phytomass (vegetation) and rainfall in Western Amazonia



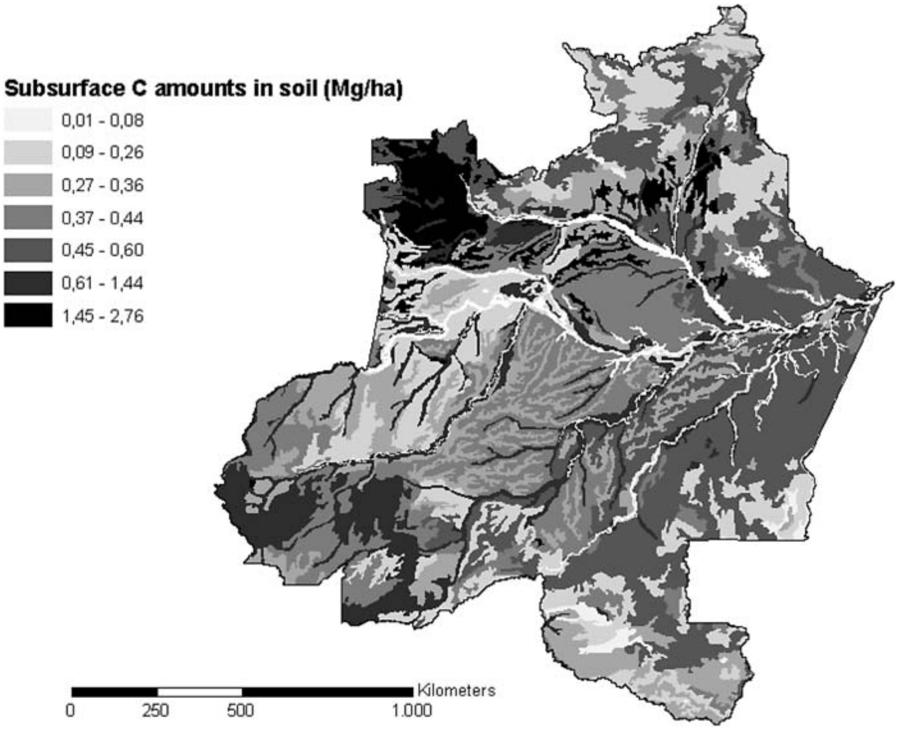


Fig. 8 Amounts of the C in subsurface horizons in Western Amazonia soils

each pedo-zone. For a given rainfall, areas dominated by deeply weathered Latosols have a pattern of higher indexes (Tertiary Plateau pedo-zone), compared with shallower soils from the upper Amazon pedo-zones, west of Madeira and Negro rivers; also, scattered areas of Latosols in Rondonia pedo-zone also show the same trend. This is consistent with a greater carbon sequestration in these Latosols, compared with

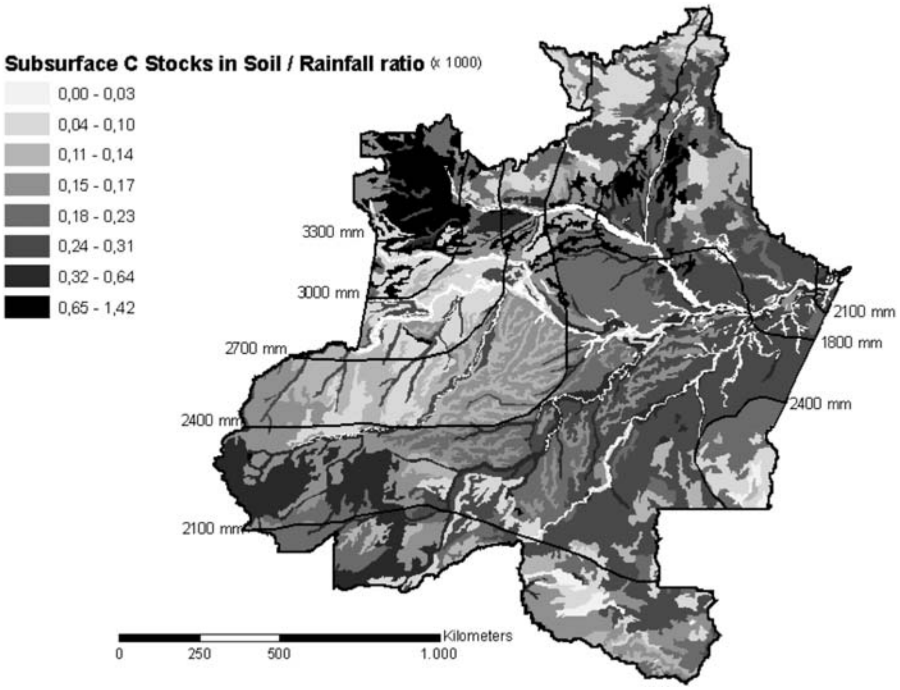


Fig. 9 Ratio between subsurface C stocks and rainfall in Western Amazonia

all other soil classes. This is attributed to a much deeper incorporation of carbon in these highly pedo-bioturbated, generally clayey soils (Schaefer 2001). This highlights the importance of biological activity for the turnover of carbon in Amazonia.

Aboveground carbon and rainfall

To best illustrate the inverse relation between plant biomass and rainfall in Amazonia, Fig. 7 shows the calculated ratio between aboveground phytomass (vegetation) and rainfall, using general climatic information; it is clearly observed a steady reduction of biomass following the climatic east–west gradient of increasing rainfall. Therefore, greater rainfall (exceeding 2,400 mm/year), associated with greater chemical leaching, sandy textures and wet-equatorial lowland surfaces, have the lowest C biomass production; this is, in turn, associated with soils in which C is being lost from the topsoil down to the spodic horizons, meaning effective C export from the natural ecosystem. This is illustrated by the widespread black rivers (tea-like) draining the Negro basin.

It should be emphasized that the abrupt lines showed in Fig. 7 are, in fact, artifacts of superimposed isoiets on a rasterized map of aboveground biomass. However, it is possible to observe a clear trend of C losses in the wetter, lowlands of western Amazonia, consistent with subsurface C amounts (Fig. 8) and the calculated ratio between subsurface C stocks and rainfall (Fig. 9).

Conclusions

The C stocks in Western Amazonia soils are extremely variable. Total C stocks are higher in the high-fertility Acre pedo-zone, where 2:1 clays with high cationic exchangeable capacity dominate, and in the Negro basin pedo-zone, where carbon is mobile, being either illuviated down the profile or actively lost from soil through extreme podzolization and arenization. High C aboveground biomass/C soil ratios are observed in the Javari-Juruá-Purus lowlands pedo-zone, where young Al-rich hydromorphic Plinthosols are found, and on the shallower soils from the highlands pedo-zones of Roraima and Rondonia.

Zones where deeply weathered Latosols dominate (Tertiary Plateau pedo-zone) have a pattern of greater C sequestration, compared with shallower soils from the upper Amazon, west of Madeira and Negro rivers. This was attributed to deeper incorporation of carbon in these clayey and highly pedo-bioturbated soils.

There is an inverse relation between plant biomass and rainfall in Amazonia, observed by calculated ratio between aboveground phytomass (vegetation) and rainfall, showing a steady reduction of biomass following the climatic east–west gradient of increasing rainfall. Thus, rainfall greater than 2,400 mm/year in western Amazonia, associated with higher chemical leaching, sandy textures and wet-equatorial lowland surfaces, have the lowest C production; in these podzolized soils, C is moving from the topsoil down to the spodic horizons, meaning effective C export from the natural ecosystem.

The results highlight the need for refining soil data at an appropriate scale, when dealing with C stocks calculations for tropical areas such as Amazonia. There is an enormous risk of misinterpreting C stocks and in Amazonia when such great variability of pedological cover is not taken into account.

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