Carbon stocks and dynamics under improved tropical pasture and silvopastoral systems in Colombian Amazonia

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A B S T R A C T
To evaluate the effect of land use change on soil organic carbon, the carbon contents and stocks of primary forest, degraded pasture, and four improved pasture systems in Colombian Amazonia were compared in a flat and a sloping landscape. The improved pastures were Brachiaria humidicola and Brachiaria decumbens, either in monoculture or in combination with native legumes. The age of the treatments was 30 years for degraded pasture and 10 or 15 years for each of the improved pastures. Carbon fractions were Total C, Oxidizable C, and Non-Oxidizable (stable) C. Stocks were compared using a fixed soil mass base. The degraded pasture in the flat landscape was abandoned and dominated by weeds, while that in the sloping area was overgrazed. The latter had much lower C stocks than the former. B. humidicola monoculture had the highest stocks both in flat and sloping areas, while the effect of the other three treatments varied. C replacement based on δ13C indicated that after 30 years, the degraded pasture still contained more than 50% forest-derived C in its topsoil. The fraction in the topsoil that is not replaced roughly coincides with the Stable C fraction. δ13C values suggest that the changes in carbon stocks ascribed to differences in land use may be at least partially inherited from the previous land use, thus confusing the interpretation of land use effects. Nevertheless, the introduction of improved pastures on degraded grassland is a feasible alternative of land use both for carbon sequestration and as an attractive economic alternative to farmers.

1. Introduction
The present paper complements the results presented in a previous one by the same authors dealing with carbon dynamics in soils of the Colombian Amazonia (Mosquera et al., 2012).

The largest potential for carbon sequestration in tropical America is in the savanna ecosystem which covers some 250 million ha, and in the tropical forest, with some 44 million ha (Amezquita et al., 2008).

Since the studies by Lugo and Brown (1993) and Fisher et al. (1994) it has been recognized that soils of well-managed tropical pasture systems may contain amounts of soil organic carbon (SOC) equal or even superior to those under native tropical forest.

Land use change in the Amazonia strongly influences soil organic matter dynamics. Thus, understanding the major effects that influence soil organic matter under cleared lands is relevant in predicting the consequences of continued conversion of tropical forest to cattle pastures and agriculture (Cerri et al., 2007). In addition, this is also important to devise management technologies/strategies to enhance the sustainability of these areas and thus slow down further deforestation.

An appropriate way to assess SOC changes in soils that have been under consecutive, vegetations with different photosynthetic pathway is the relative abundance of the stable isotopes 13C and 12C, expressed as δ13C (Balesdent and Mariotti, 1996). Plants with a C3 photosynthetic pathway (virtually all trees, shrubs, and grasses of temperate climates) discriminate more against 13C than those with a C4 photosynthetic pathway (largely tropical grasses). SOC inherits the isotopic signature of the litter, and thus reflects the standing vegetation, both above- and belowground. In C3 systems there is a significant increase of δ13C from litter to topsoil, and therefore, calculations of replacement by C3 humus should be based on the δ13C value of the topsoil rather than that of the litter (e.g., Roscoe et al., 2002).

Land use conversions in tropical savannahs or pastures are suited for isotope studies of C dynamics (Ehleringer et al., 2000). For the Amazonian systems, this is true, because 1) the forest to pasture conversion is a C3–C4 transition; 2) the degradation of pasture causes an increase of C3 shrubs in a C4 pasture, 3) the establishment of improved grass monocultures is a reversion to C4, and 4) establishment of fodder banks is a reversion to C3 vegetation.
In general, land use transition studies employing δ13C data have focused on δ13Csoil in forest to pasture transitions. There have been a few studies concerning recovery of degraded pastures, but little work has been done with δ13Csoil in these systems (Schellbauer and Kavanagh, 2008). The present work presents differences in carbon contents and stocks related to changes in land use and tries to link such differences to SOC dynamics.

2. Materials and methods

Areas of representative land use systems were chosen on four farms in the Amazonian humid tropical forest, both on flat and mildly sloping topography, at 800 m.a.s.l., 1.8° N, 75.7° W, with an annual precipitation of 3500–4000 mm. Soils of the region are acid (pH<5) and have low phosphorus content and high aluminum saturation. The soils of the flat areas are Haplic Acrisols, while those in the mild slope areas are Haplic Ferralsols (Manneje et al., 2008). General soil characteristics are given in Table 1.

Blocks of different land uses (treatments) were chosen within the farms where the history of land use had been documented. These were “La Guajira”, a well managed commercial livestock farm (250 ha) and “Santo Domingo” a poorly managed experimental farm (60 ha) with degraded pastures, for the flat area, and “Los Balcanes” a poorly managed experimental farm (60 ha) with degraded pastures and “Pekin” a well managed commercial livestock farm (800 ha) for the sloping landscape; the four farms were located nearby Florencia, Caquetá, Colombia. The different land uses (treatments) were natural forest, degraded pasture, and four improved pastures, i.e., Brachiaria humidicola in monoculture; Brachiaria decumbens in monoculture; B. humidicola + legume; B. decumbens + legume. The improved pastures were all established in previously degraded pasture. The age of the various systems was different: More than 80 years for the forest, about 40 for the degraded pastures and 10–15 for the improved systems. On each land use system, linear transects of 1000 m were marked in the direction of the predominant slope gradient. Four main sampling points (major profile pits of 150×100×100cm) were located along the transect and eight secondary sampling points, were located on each side of the main sampling points perpendicular to the gradient. Soil samples were taken at four depths 0–10, 10–20, 20–40 and 40–100 cm, for a total of 48 samples per treatment. Triplicate samples for bulk density were taken from the same layers by the core method. Surface litter was also sampled at each sample location.

Carbon determinations were carried out in the Analytical Services Laboratory at CIAT (Centro Internacional de Agricultura Tropical) Cali, Colombia. Total and Oxidizable Carbon were determined according to Laboratory at CIAT (Centro Internacional de Agricultura Tropical) Cali, Colombia. Total and Oxidizable Carbon were determined according to Walkley–Black modified by Kurmies (Temminghoff et al., 2000). In short, Oxidizable C was determined by oxidation with K2Cr2O7 in H2SO4 at room temperature, and measurement of the resulting chromic ion by spectrophotometer at a wavelength of 585 nm. Total C was measured using the same oxidant at a temperature of 120 °C during 2 h.

The isotope (δ13C) analyses were carried out at the University of Davis-Isotope Facility, California. The 13C content of a sample is expressed relative to a geological standard, the PeeDee belemnite, or its gas equivalent, the Vienna PDB, as follows: δ13C (per mil) = 1000 × (13Rsample – 13Rstandard) / 13Rstandard, in which 13R is the 13C/12C ratio. As the δ13C of any soil sample is a linear mixture of the contributions from C3 and C4 vegetation, the relative contributions of each can be calculated from δ13Csample = x × δ13Cc3 + (1−x)×δ13Cc4, in which x is the fraction of C3-derived SOC, (1−x) the fraction C4-derived, and the δ13C values denote the typical means of the relevant C3 and C4 litter.

For a valid comparison of Carbon stocks between land uses, the calculations were based on fixed soil mass (Ambeziquita et al., 2008; Ellert et al., 2002). The results are given in t.ha−1.meter-equivalent−1 (m-equiv is the soil mass of the profile that had the lowest mass to 1 m depth). The formula for this calculation is as follows:

C stock = 10 × (C0−10 × BD0−10 + C10−20 × BD10−20 + C20−40 × BD20−40 + (WR − W0−40) × C40−100), in which:

C = C content of specific layer (g.kg−1),
BD = bulk density of specific layer (kg.dm−3),
W0−40 = weight of upper 40 cm of present profile in kg.m−2,

Data were statistically analyzed by SPSS 11.5. An Anova was used to determine statistical differences between treatments.

3. Results and discussion

3.1. C contents

Carbon contents for each of the four depth sections are presented in Table 2. Surprisingly, in the flat area the lowest carbon contents in all layers were found under primary forest, while in the sloping area, the primary forest has the highest contents in all layers. It is possible that the forest plot in the flat area is not a proper reference because it was located far from the other plots – no forest remained close by – and exhibited bad drainage which was not found in the other plots of the flat area.

If degraded pasture is taken as a reference, in the flat area all improved pastures but B. decumbens monoculture showed some increase in C contents in the surface layer. The smallest effect was found under B. decumbens + legume and the biggest under B. humidicola monoculture. In the 10–20 cm layer no difference between C contents was detected; in the 20–40 cm layer the values for B. decumbens were lower than those for degraded pasture, while no difference was detected between B. humidicola and degraded pasture.

Table 1

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>pHH2O</th>
<th>TOC a</th>
<th>PReq e</th>
<th>Exch. Al</th>
<th>Exch. Ca</th>
<th>Exch. Mg</th>
<th>Exch. K</th>
<th>B.D. h</th>
</tr>
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<tbody>
<tr>
<td>Flat topography</td>
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<td></td>
</tr>
<tr>
<td>0–10</td>
<td>4.7</td>
<td>25.8</td>
<td>3.09</td>
<td>3.12</td>
<td>0.13</td>
<td>0.06</td>
<td>0.18</td>
<td>1.05</td>
</tr>
<tr>
<td>10–20</td>
<td>4.6</td>
<td>17.3</td>
<td>0.85</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>1.22</td>
</tr>
<tr>
<td>Sloping topography</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–10</td>
<td>4.6</td>
<td>24.7</td>
<td>1.93</td>
<td>8.53</td>
<td>0.64</td>
<td>0.22</td>
<td>0.26</td>
<td>1.12</td>
</tr>
<tr>
<td>10–20</td>
<td>4.9</td>
<td>15.1</td>
<td>0.82</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>1.31</td>
</tr>
</tbody>
</table>

a TOC = total organic carbon.

b B.D. bulk density.

c n.d. = not determined.
In the sloping area, all improved pastures showed a significant increase in C, with respect to degraded pasture, in the top layer, while both B. humidicola monoculture and B. decumbens + legume showed an increase throughout the profile.

In both landscapes, most improved pastures showed a significant increase of C contents in the 0–10 cm layer with respect to the degraded grassland. Increases in C content in surface horizons after conversion to pasture have been often reported for the Amazon area (e.g., Neil et al., 1997; Trumbore et al., 1995), de Moraes et al. (1996) found that, in the western part of Brazilian Amazonia, total soil C contents to 30 cm in 20-year-old pasture were 17–20% larger than in the original forest sites. Some studies report soil C content decline (Desjardins et al., 2004) or a conservation of the initial C content (Buschbacher et al., 1988). Pasture management probably plays an important role in C accumulation or loss, as reported by Trumbore et al. (1995) and Fernside and Barbosa (1998).

3.2. C stocks

Carbon stocks based on fixed soil mass are given in Table 3. Separate calculations were made for Total C (TC), easily Oxidizable C (OxC) and Non-Oxidizable (stable) C (NOxC). Stocks of NOxC are obtained by subtracting stocks of OxC from those of TC.

In both areas there are wide differences between stocks under the various treatments. In the flat area, stocks range from 104 to 137 in 1 meter-equivalent (Table 3). Highest stocks were found in soils where the C contents remain higher in the layers below 20 cm, i.e. B. humidicola, B. humidicola + legume, and degraded pasture in the flat landscape, and forest, B. humidicola, and B. decumbens + legume in the sloping landscape. In the flat topography, the degraded pasture belongs to the group with the highest C stocks, while it belongs to the lower group in the sloping area. This is mainly due to the fact that ‘degraded pasture’ is a varying concept. In the flat area, as shown by the 13C signature of the vegetation (Table 4), it denotes a pasture that is largely colonized by shrubs; while in the sloping area it is still dominated by grasses and over-grazed.

In the flat landscape, the primary forest had the lowest Total Carbon stocks, while the degraded pasture and both improvements with B. humidicola had the highest. It was already mentioned that the flat land forest, because of its impeded drainage, is not a proper reference for other flatland soils. Poorly drained soils may have lower C contents than better drained ones close by, as also found for grassland soils invaded by shrubs in the US (Albrecht and Kandi, 2003).

Both B. decumbens pastures had significantly lower C stocks than the degraded pasture. Because TC and OxC contents are highly correlated ($r^2 = 0.93–0.98$), Oxidizable C showed the same pattern. The highest stock of NOxC was found under $B. humidicola$ monoculture.

In the sloping area, highest stocks were found under forest, B. decumbens + legume and B. humidicola in monoculture. Stocks under both B. decumbens monoculture and B. humidicola + legume were significantly lower but not different from that under degraded pasture.

NOxC stocks are between 42 and 52% of TC stocks in the flat area and between 40 and 48% in the sloping area. The level of the NOxC stocks increases with that of the total stocks.

The various treatments do not appear to have the same effect in the two topographies, except for the B. humidicola and B. decumbens monocultures, each of which had similar stocks in both topographies. The forest treatment showed the lowest content in the flat area. In sloping areas however, forest showed the highest TC content and B. humidicola + legume and B. decumbens, the lowest but similar to that in degraded pasture. With respect to the NOxC contents, in flat landscape all treatments have stocks significantly higher than that in forest, with that in B. humidicola the highest. In the sloping landscape, degraded pasture and B. humidicola + legume showed the lowest and forest and B. decumbens + legume the highest.

Comparing the Total C stocks of the improved pastures with those of the degraded pasture, it appears encouraging that in sloping areas B. humidicola and B. decumbens + legume showed increases of 40 to 50 t ha$^{-1}$. This difference was obtained in (less than) 15 years. In both the flat and sloping area, high stocks are related to high C contents throughout the profile.

In flat areas, improved pastures did not increase C stocks when compared with degraded pasture, but this was mainly due to a vigorous regrowth of native shrubs in this degraded pasture.

In general, decreases of soil carbon stocks occur when forests are converted to other land uses, but there are contrasting reports on the effects of forest to pasture conversion. Powers and Veldkamp (2005) found that mean values of soil C stocks were similar under primary forest (80.5 Mg C ha$^{-1}$) and pasture (76.7 Mg C ha$^{-1}$) across a
large region in Costa Rica (1400 km²), though variation was high within the region and best explained by topographic features and soil mineralogy. In our case, there were differences in soil properties between the flat and the sloping area (Table 1). In the sloping area, although the soils are generally more weathered than in the flat area, both nutrient and Al contents were higher. The first is conducive to biomass production, while the second helps SOC preservation in the soil through organo-mineral associations. Whether a soil under pasture behaves as a net C sink or will probably depend upon management. Previous studies in grasslands under‘typical’management practices indicate that pasture soils in Brazilian Amazonia behave as a net C source, with an estimated average release of 12.0 t.C.ha⁻¹.y⁻¹ (Boutton and Yamasaki, 1996). The litters, reflecting the standing vegetation, which is mostly a mixture of C3 and C4 plants. The B. humidicola litter appears rather pure, as it has a similar δ¹³C in both the flat and the sloping area. The B. decumbens litter shows a large variation, depending on the admixture of C3 vegetation. For replacement calculations, we used only the value (−13.33) that appears to reflect a pure C3 vegetation. ¹³C signatures of the B. decumbens + legume mixture are necessarily quite variable. We report the measured values, but for replacement calculations we used the value of −16.80, which is the mean value encountered in the B. decumbens + legume mixture of the flat landscape. This is, of course, an arbitrary choice but suitable for our approach.

Also the variation in litter δ¹³C of the degraded pastures was significant, reflecting the difference between degraded grassy vegetation and regrowth of C3 shrubs. For calculations of remaining forest C in the degraded grasslands, we used the value of −13.96 that was encountered in the sloping area, because the conversion was from forest to grassland. The replacement calculations encompass the following comparisons:

- Forest to degraded pasture: the amount of remaining forest-C after 40 years of pasture. For C4 contribution, the δ¹³C value of the litter of the degraded pasture of the sloping area was used.
- Degraded grassland to improved pasture: the influence of the new C4 contribution can only be properly measured under the monocultures. For contribution of the new vegetation, the values given in ¹³C than C3 litter (e.g. Dijkstra et al., 2006). It cannot be ascribed to an accumulation of relatively recalcitrant compounds, because such compounds tend to have a lower δ¹³C than the less recalcitrant ones (Boutton and Yamasaki, 1996).

3.3. ¹³C signature and replacement

The values of the ¹³C signature (Table 4) for the litters of the different land uses were typical for the kind of vegetation they represented: −30.37 and −30.42 for forest in flat and sloping areas, and −13.33 and −12.93 for B. humidicola in monoculture. Values of −30% and −27% have been found for Brazilian forest (Feigl et al., 1995) and woody savanna litters (Roscoe et al., 2000). The two forest profiles behave similarly. As common in forest soils, there is a significant increase in ¹³C from litter to topsoil, after which ¹³C contents increase gradually with depth (Roscoe et al., 2000). This increase is largely due to an admixture of microbial C, which has a higher δ¹³C than C3 litter (e.g. Dijkstra et al., 2006). It cannot be ascribed to an accumulation of relatively recalcitrant compounds, because such compounds tend to have a lower δ¹³C than the less recalcitrant ones (Boutton and Yamasaki, 1996).

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- Degraded grassland to improved pasture: the influence of the new C4 contribution can only be properly measured under the monocultures. For contribution of the new vegetation, the values given in

### Table 4

| Soil δ¹³C values (%) under different land use systems on flat and sloping areas.¹
<table>
<thead>
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<tr>
<td>Depth (cm)</td>
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<tr>
<td>Litter measured</td>
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<tr>
<td>Litter used</td>
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<tr>
<td>Slope</td>
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<td>0–10</td>
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<td>20–40</td>
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<td>40–100</td>
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<td>Sloping</td>
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<tr>
<td>Litter used</td>
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<tr>
<td>0–10</td>
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<tr>
<td>20–40</td>
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<td>40–100</td>
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</tbody>
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¹ Different letters denote statistically significant differences (p<0.05) within one topography and within one row. (Standard deviations between brackets).

### Table 5

| Remaining C fraction, means and standard deviations.²
<table>
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<tr>
<td>Depth (cm)</td>
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</tr>
<tr>
<td>Flat landscape</td>
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<tr>
<td>10–20</td>
</tr>
<tr>
<td>20–40</td>
</tr>
<tr>
<td>40–100</td>
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<tr>
<td>Sloping landscape</td>
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<td>10–20</td>
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<td>20–40</td>
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<td>40–100</td>
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</table>

² Remaining degraded pasture fraction.
³ Remaining native forest fraction.
After about 40 years, the degraded pasture in both topographies retains about 55% of forest C in the topsoil. This is consistent with 40–50% non oxidizable C as indicated above. The influence of the pasture decreases with depth, but reaches deeper in the flat than in the sloping area. A replacement of about 50% in the topsoil in a period of 10–30 years is quite common. Similar values were found for converted Brazilian Amazon forest (Choné et al., 1991; Trumbore et al., 1995) and for converted Brazilian Cerrado forest (Roscoe et al., 2000).

The replacement under the improved pastures with respect to the degraded pasture can only be properly measured in the monocultures. The replacement in the sloping area appears to be larger and deeper, but this is probably due to the fact that the improved pastures in the flat area had an age of 10 years, while in the sloping area this was 15 years. In addition, the B. decumbens pasture in the flat area had been severely neglected. There is a significant replacement under B. humidicola in the sloping area, but only in the topsoil in the flat area. Similarly, the effect of B. decumbens cannot be traced in the flat area and is rather low in the sloping area. The B. humidicola + legume pastures showed significant replacement at all depths for both topographies. In the flat area, the effect of B. decumbens + legume is significant in the upper two layers — and this is a minimum effect because legume-C cannot be identified. In the sloping area, the replacement under B. decumbens + legume is low in the topsoil, but this may be due to a large contribution of C4 weeds in the present vegetation (compare Table 4).

Because C replacement in the soil under pasture is primarily linked to deposition of root litter carbon, a relation between replacement and changes in stock should be expected, but the results are not unequivocal. In three cases, i.e. B. humidicola monoculture and B. decumbens + legume in the sloping area, and B. humidicola + legume in the flat area, considerable C replacement throughout the profile depth coincides with high C stocks, but B. humidicola + legume in the sloping area shows a significant replacement without the accompanying high C stock, while B. humidicola in the flat area combines low replacement with high C stock. One complicating factor is that an addition of new C without any replacement of old C would also result in a calculated ‘replacement’. Such effects can only be found when C contents are taken into account and not just the fraction of old C remaining in the system. This, however, is not a major factor, because higher C contents (with respect to degraded grassland) in subsoils do not coincide with significant replacement. Comparing Tables 2, 3 and 5, we can conclude that high C stocks under B. humidicola and B. decumbens + legume in the sloping area, and B. humidicola in the flat area, do not show significant replacement in the high-C subsoil layers. We must therefore conclude that these differences were inherited from the previous land use.

4. Conclusions

Although improved pastures tend to have carbon contents and stocks that are superior to those in degraded pastures, the differences are sometimes obscured by variation in the concept of degraded pasture. If pastures are overgrazed, they tend to have low carbon stocks, but if they are abandoned or undergrazed, weeds tend to establish and carbon stocks can go up considerably.

Of the four improved systems investigated here (B. humidicola and B. decumbens in monoculture and in combination with legumes), only the B. humidicola monoculture increased C contents and stocks both in the flat and the sloping landscape. The other combinations had varying success, but the variation is partly due to different time from establishment and different management.

Replacement calculations indicate that, after 30 years, 50% of the C in the topsoil of the degraded pasture was still forest derived. This suggests that the fraction that is here called ‘stable C’ is not affected by this medium term replacement.

Significant increases in C stock should be reflected in a change of the 13C signature of the Total C. Some treatments did not show such a coincidence, and this suggests that differences in C stock ascribed to the cultivation system may in fact reflect inherited variations in the soil. This is a major – and so far unexposed – problem in the interpretation of land use effects on C stocks. To fully understand the carbon dynamics in the tropical environment, not only C stocks and replacement should be studied, but also the effect of topography, climate, soil characteristics, and differences in management, which all influence the cycling of soil organic matter.

Acknowledgments

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