Recent history of the agriculture of the Brazilian Amazon Basin

Prospects for sustainable development and a first look at the biogeochemical consequences of pasture reformation

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Abstract: *Land-use change for human settlement and agricultural purposes, especially pasture establishment, has caused major impacts on the Amazon Basin's environment. Development of strategies for reformation and restoration of already degraded pastures constitutes the main goal of the authors' research work. For some of this work, a homogeneous area of land in terms of soil characteristics was selected at Nova Vida ranch in Rondônia state to conduct a multidisciplinary experiment, which included agronomic, environmental and economic analyses. Since July 2001, the authors have monitored five treatments: control, herbicide, tillage, no-till rice and no-till soybean, arranged in four blocks. Early results on carbon and nitrogen stocks, nitrogen mineralization, trace-gas fluxes, dissolved organic carbon and microbial biomass are briefly presented.*

Keywords: *pasture reformation; management options; soil properties; Amazonia; Amazon Basin*

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The Amazon Basin covers an area of 7,050,000 km^2 (5°N, 17°S; 75°W, 46°E) and occupies portions of the national territories of Bolivia, Brazil, Colombia, Ecuador, Guyana, Peru, Surinam and Venezuela. A major fraction of the Basin, about 5,000,000 km^2, is in Brazil (Pires and Prance, 1986).

In recent decades, human settlements in the Brazilian Amazon have grown at an exponential rate. Its population has grown by 130% since the 1970s, reaching approximately 19 million in the year 2000. Rondônia state has experienced the most rapid growth over the past few decades. During the period 1968–78, an average of 25,500 people migrated to the state each year. This number increased to 65,000 yr^{-1} during the period 1980–83, and 160,000 yr^{-1} during 1984–88 (Moran, 1992). The exponential settlement rate and associated land-cover changes have caused impacts on biodiversity, carbon storage and regulation of the water cycle (Fearnside, 1997).

These environmental impacts have caused concerns about the sustainability of land use in the Amazon region. Sustainable development of the Brazilian Amazon has become a topic of national and international debate that has involved policy makers, scientists and environmental advocates.

Sustainable development is an important issue in the Amazon region, not only because the region contains about 40% of the world's remaining tropical rainforest (Laurance *et al*, 2001), but also because it represents one of the richest areas of biodiversity in the world (Mesquita *et al*, 1999; Chambers *et al*, 2000).

The sustainable-development issue for the Brazilian Amazon was considered in the 'Avança Brasil' Program (ABP), which outlined projects in a number of areas including social development, economic infrastructure and environmental management, with the goal of optimizing the development of the Basin in a sustainable way.

Some NGOs have criticized the ABP's plan for the Amazon region because, they argue, it has the potential to cause large-scale ecological and social damage. Before implementing the ABP plan, it seemed wise to conduct a thorough evaluation of its potential impact and to engage the project's myriad stakeholders in discussions of how best to minimize negative effects and maximize benefits. According to Instituto de Pesquisa Ambiental da Amazônia (IPAM, www.ipam.org.br/), the ABP will lead to the clear-cutting (deforestation) of 120,000 to 270,000 km^2 of primary forest over the next 25 to 35 years. Considering the concerns about implementing the ABP, an important mission now is to find sustainable solutions in the struggle between the ideals of rainforest preservation and the realities of life.

The Community Initiative Program (CIP), part of the PLANAFLORO regional development programme in the western Brazilian Amazon state of Rondônia (Browder, 2002) is designed as a positive action to achieve sustainable development. The original goal was to implement an improved approach to natural resource management, conservation and sustainable development through the introduction of agroecological and socioeconomic zoning in the state.

History of Basin development

The colonization of the Amazon region started at the beginning of the sixteenth century with the arrival of the Spaniards in the west and the Portuguese in the Atlantic east. Between then and the end of the Second World War, no major changes in the Basin's natural environment occurred.

Throughout the 1950s and 1960s, the Amazon received a small but steady influx of 'spontaneous' immigrants, as agriculture and livestock activities moved westward into the states of Maranhão and northward into Goias and Mato Grosso, replacing the southern states of Paraná and Rio Grande do Sul as Brazil's new frontier (Goodman and Hall, 1990).

The main changes in the Basin's ecosystems began after 1970, when important mineral deposits including iron, aluminium, tin and gold were discovered. However, it is probable that large agricultural programmes promoted by either official entities or private companies have had a much greater ecological impact than any other human activity (Fearnside, 1986).

The establishment of the Belém–Brasilia highway opened the forest frontier in Paragominas to harvesting and wood-processing activities about 30 years ago. During the 1970s and 1980s, the industry grew rapidly, largely due to agricultural subsidies that induced conversion of forests to pastures. During the 1990s, expansion of the wood-products industry slowed, many less well organized companies disappeared to be replaced by better capitalized firms with expanded processing capacity, and some firms established export clearing houses (Goodman and Hall, 1990). As the wood-products industry matured, the most accessible timber stocks were depleted, log-hauling distances increased, and firms began using larger trucks to help control transportation costs. Between 1990 and 1995, delivered log prices increased by 10–30% and stumpage prices doubled. Furthermore, both the policy bias in favour of large landed interests and high inflation rates encouraged the consolidation of land ownership in every successive Amazon forest frontier zone (Fearnside, 1986).

The dominant land use is agriculture including: shifting cultivation, intensive cropping of perennial plants, with or without annual-crop interplanting, and pasture installation (Andreux and Cerri, 1989). In the case of shifting cultivation, the deforested area is used for two to four years, mainly for the production of manioc, beans, rice and maize, then the soil generally becomes unproductive and has to be abandoned. The secondary vegetation that develops when the soil is in fallow is called *Capoeira*. If left alone, the *Capoeira* will develop into a forest ecosystem, although not necessarily as diverse as the original forest (Pires and Prance, 1986). 'Intensive cropping' refers to the production of short-cycle crops in a continuous and permanent way, either as monoculture or crop rotation. Among the perennial crops installed in the region, pepper, cocoa and guaraná (*Paullinea cupana*) are the most important (Andreux and Cerri, 1989). Clear-cutting of forest areas to establish managed pastures is probably one of the most controversial activities in terms of potential risk for the Amazon's natural ecosystems (Fearnside and Barbosa, 1998; Graça *et al*, 1999; Fearnside, 2001).

The total size of the deforested area is much debated. The Brazilian government's estimated value for the extent

Figure 1. Degraded pasture area.

of gross deforestation is 587,727 km^2, which corresponds to approximately 12% of the total Brazilian Amazon area (INPE, 2000). Skole *et al* (1994) and Fearnside and Barbosa (1998) estimated that 75% of the deforested land had been managed as pasture at one stage or another, whereas 45% was converted directly to pasture (Fearnside, 1996).

Generally, five to ten years after deforestation, pastures become degraded due to bad management practices. These practices have long been recognized as one of the major causes of on-site fertility reduction, as well as soil compaction, a decrease in water supply, soil erosion and nutrient-loss acceleration. Off-site consequences may include the increase of CO_2 fluxes to the atmosphere, with increasing organic-matter mineralization as well as a decrease in groundwater recharge, pollution of groundwater and surface waters by nutrients, and erosion, with soil deposition in valley bottoms and reservoirs (IGBP, 1995). All these effects may seriously jeopardize the sustainability of natural ecosystems and agricultural systems.

According to Serrão and Homma (1993), more than 100,000 km^2 of the pastures in the Brazilian Amazon present some level of weed invasion, which characterizes a high degree of degradation (Toledo and Navas, 1986).

Since grazing for beef, and to a lesser extent dairy production, is the largest single agricultural activity on cleared land in the Amazon, it demands greater critical research attention than it has so far received.

Decline in pasture productivity

Pastures make up the principal use of cleared land in the Brazilian Amazon. Observations show that 4 to 10 years after they are formed, pastures generally begin a process of degradation that is characterized by a decline in grass productivity and an increase in the cover of weeds (Figure 1). For both environmental and economic reasons, development of strategies for reformation and restoration of these existing degraded pastures is preferable to formation of new pastures by traditional slash-and-burn activities.

Degradation of pastureland is generally the result of ranchers imposing stocking levels that exceed the carrying capacity for cattle (Dias-Filho *et al*, 2001). High stocking levels often lead to changes in soil physical and chemical properties (Moraes *et al*, 1996; Neill *et al*, 1997a). Desjardins *et al* (2000) pointed out that pasture management, ie choice of the forage grass species, control of the carrying capacity, use of fire or cutting to control the secondary vegetation all strongly influence the evolution of pasture.

Overgrazing causes inadequate grass-regeneration conditions, especially because both root and leaf are often consumed by the animals. Once the grass cover in a pasture becomes sparse, weed invasion begins. If this condition persists for two or more years, the weeds become dominant and the grass productivity is drastically reduced, the degraded pastures lose their economic viability and are abandoned.

Pasture degradation related to changes in soil physical properties is mainly due to the exposure of the surface layer to the direct impact of raindrops and cattle compaction, which cause an increase in soil bulk density and a decrease in clay flocculation and soil total porosity. Roots grow poorly under these altered conditions. The lack of soil phosphorus availability is the most limiting factor to the maintenance of grass productivity (Dias-Filho and Serrão, 1987; Serrão *et al*, 1982; Souza Filho *et al*, 1991; Veiga and Serrão, 1987).

Availability of soil nitrogen is another important limiting factor that contributes to a reduction in pasture productivity, and in some cases, abandonment. Nitrogen cycling processes clearly change during the time of pasture installation (Dias-Filho *et al*, 2001; Piccolo *et al*, 1996; Neill *et al*, 1995, 1997b, 1999). Nitrogen turnover gradually declines as pastures age (Neill *et al*, 1995, 1997a,b). Rates of net mineralization and net nitrification are consistently lower in soils of three years old or in pastures older than those in the forests from which they were created. Forest clearing for pasture can increase N_2O emissions for a post-clearing period (less than 2–10 years), while older pastures often exhibit lower emissions than the original forest (Keller *et al*, 1993; Garcia-Montiel *et al*, 2001; Melillo *et al*, 2001). The lower N_2O fluxes from pasture are associated with lower nitrate pools and lower rates of net N mineralization and nitrification. Low nitrate production in pasture soils results in small losses from soil to soil solution and stream water (Neill *et al*, 2001).

Pasture reformation by fertilizing with nitrogen and phosphorus, tilling and liming can influence N_2O fluxes. Fertilizing could increase N_2O emissions directly by increasing N availability (Matson *et al*, 1998; Steudler *et al*, 2002). Tilling also could increase the emissions by increasing N availability, by removing plant demand, and by increasing the availability of labile carbon to fuel denitrification.

Ayarza (1991) pointed out that besides P and N, other nutrients, such as Ca, Mg, K, S, B, Cu, Zn and Mo, could also be limiting factors to the grass growth, enhancing pasture degradation.

Pasture degradation can lead to negative economic, social and environmental consequences. Under normal conditions, animal carrying capacity for the Amazon region is, on average, one to two animals per hectare. Reduced pasture productivity leads to a decrease in stocking density. Lower stocking densities result in reduced profits for ranchers and cause social problems due to increases in unemployment among ranch workers. In order to maintain profitability, ranchers often clear more forests to replace the abandoned areas, and this activity is one of the major causes of continued deforestation in the Amazon.

Pasture restoration and management options

There are alternatives to pasture degradation and subsequent abandonment. Ranchers could reduce overgrazing, control weeds and maintain soil fertility to maximize plant growth, and thereby eliminate the economic, social and environmental problems. Once a pasture has reached the degraded stage, ranchers can use a range of agronomic techniques to restore pasture productivity. These techniques include herbicide applications to eliminate weeds, disking and ploughing, applying mineral fertilizers and in some cases liming, reversing soil compaction using deep-rooted legume plants that simultaneously introduce nutrients through plant-residue decomposition (Arruda *et al*, 1987; Barcellos, 1990; Carvalho *et al*, 1990; Kluthcouski *et al*, 1991; Soares Filho *et al*, 1992; Veiga, 1995).

The ‘Barreirão system’ adopted by EMBRAPA, that is, soil cultivation followed by grass and rice seeding, has been used successfully as a pasture-reformation scheme (Kluthcouski *et al*, 1991; Oliveira *et al*, 1996). Soy beans are another cash crop that can be used in the Barreirão system. They have the advantage of incorporating nitrogen into the soil by symbiotic fixation.

How did we choose between several management options?

In order to contribute to the sustainable development of the Amazon region, degraded pasture areas should be restored to become productive. This would reduce the need for clearing new natural ecosystems.

There are a number of strategies for restoring degraded pasture that will depend for their success on adaptation to local conditions. In addition to strategies for adapting to and utilizing the soils effectively, there are related environmental factors that need careful examination, such as the rainfall-evapotranspiration regime, drainage patterns and relief, local plant adaptations and nutrient-conservation mechanisms, plus a host of socioeconomic considerations such as access, transportation, markets and social traditions.

Most scientists and observers appear to agree on the need for conserving the environment while allowing controlled development. The difficulty lies in finding agreement on the precise definitions and strategies for such development. Soil management has a pivotal role to play in the quest for economic growth in a way that maintains or improves the environment. We need new integrated assessments that consider the environmental, agronomic and economic consequences of various strategies for pasture reformation.

A case study at Nova Vida ranch

A multidisciplinary and inter-institutional consortium of scholars from CENA and ESALQ / USP-Brazil, EMBRAPA-Brazil, the Ecosystem Center-USA and IRD-France is conducting an experiment to test different strategies for the restoration of degraded pastures at Nova Vida ranch in central Rondônia.

The main objective of this study is to examine strategies for recuperation of degraded pastures in Amazonia using agronomic, environmental and economic criteria. To achieve this objective, we are conducting an experiment on a 63 ha area of pasture that is in the process of degradation, located at Nova Vida ranch (Figure 2).

Experiment design

To ensure that this experiment was located on a representative and homogeneous area of the existing pasture, the 63 ha area was characterized for topography, soil physical and chemical attributes, production and nutritive value of existing forage plants, weed infestation and botanical composition. In this area at Nova Vida ranch, a total of 3,000 soil samples was collected from several depths (0–10, 10–20 and 20–30 cm layers), analysed and the results interpreted using geostatistic procedures. Maps of soil physical and chemical properties, as well as topography and soil types, were integrated using geographic information systems (GIS) (Cerri *et al*, 2004).

The experiment consists of five pasture reformations arranged in four blocks (replicates), as indicated in Figure 3. Each one of the 20 plots has an area of 1,600 m^2 (40 × 40 m), totalling a study area of 3.2 ha.

The five treatments were: control (C); herbicide (H); tillage (T); no-till rice NT(R); and no-till soybean NT(S). In September 2001, before implementing the different management strategies, all woody vegetation larger than 10 cm in diameter was eliminated by cutting and removing the material from each plot to facilitate the management practices and homogenize the initial above-ground inputs. Then the herbicide picloram (2% in water) was applied to the stumps. Afterwards, the remaining vegetation in the four blocks was mowed at 40 cm high. The cut part was left on the soil surface. The descriptions of specific management practices for each treatment are presented below.

Treatment C. No other management was done.

Treatment H. Elimination of the remaining weeds was done using 4 l ha^{-1} of the herbicide 2,4-D Triet. + picloram applied using three spreaders (Condor Pec Jacto) with 300 l ha^{-1} flow achieving 10 m wide with each pass.

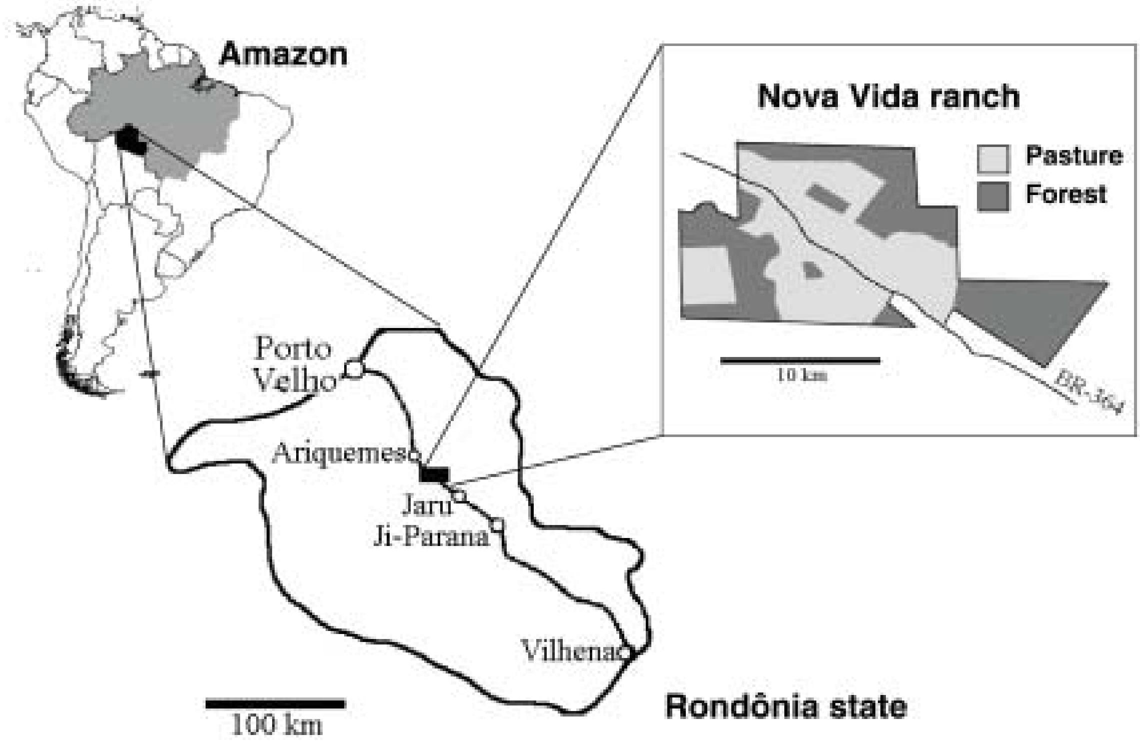

Figure 2. Nova Vida ranch.

Fertilizer (top-dressing) was applied manually at the soil surface, as follows: 200 kg ha^{-1} of ammonium sulphate, 50 kg ha^{-1} of KCl, and 30 kg ha^{-1} of micronutrients, corresponding to 32, 8 and 4.8 kg respectively in each plot (40 × 40 m).

Treatment T. Disking was done twice, in early and late October 2001. Offset disk harrows were used immediately after the second disking. Basic application of 1,020 kg ha^{-1} of termophosphate fertilizer was carried out in early November, followed in early December by top-dressing equal to treatment H. The variety 'Pastofort' of *Brachiaria brizantha* was seeded at a density of 30 kg ha^{-1}. Post-emergent herbicide 2,4-D Triet. + picloram for wide leaves (3 l ha^{-1}) was applied in January 2002.

Treatment NT(R). This treatment involved complete desiccation of degraded pasture vegetation, fertilizer application, no-tillage seeding of rice followed by *Brachiaria brizantha* cultivation. The desiccation involved two different herbicide applications. The first, glyphosate (7.5 l ha^{-1}) and 2,4-D Triet. + picloram (5 l ha^{-1}) mixed with mineral oil (2 l ha^{-1}) were applied at the beginning of the third week of October 2001, using three Condor Pec Jacto spreaders with 300 l ha^{-1} flow, achieving 10 m wide with each pass. The second application was applied at the beginning of the second week of November 2001 and consisted of 6.9 l ha^{-1} of paraquat using a Condor Pec Jacto spreader with 420 l ha^{-1} flow. At the time of the herbicide application, the temperature was 30°C and the humidity was around 75%. Two sets of fertilizer were applied. The first was at the beginning of the first week of November 2001 and consisted of base application of 531 kg ha of termophosphate. At the same time, 90 kg ha^{-1} of rice seed, precocious variety 'Primavera', treated with 300 ml in 80 kg ha^{-1} of carboxin and 1 l in 80 kg ha^{-1} of thiodicarb to avoid fungi and insect attack, was also applied. At the end of November 2001, a mixture of the herbicide paraquat and formicide fipronil was applied. A top-dressing of 60 kg ha^{-1} ammonium sulphate, 80 kg ha^{-1} of KCl and 30 kg ha^{-1} of micronutrients was applied. After the rice was harvested, *Brachiaria brizantha* variety 'Pastofort' (purity of 40%, germination 805) was seeded. In mid-December 2001, the post-emergent herbicides ethoxysulfuron and metsulfuron methyl were spread manually at a rate of 87.7 g ha^{-1} and 7.5 g ha^{-1} respectively. At the same time, 0.02 l ha^{-1} of formicide fipronil was applied. At the beginning of January 2002, a foliar application of zinc sulphate (0.4 kg ha^{-1}) was completed. At the same time, 100 kg ha^{-1} of ammonium sulphate as a differential primordial floral (DPF) treatment and 35 kg ha^{-1} of KCl were applied. The pesticides chloropyrifos (1 l ha^{-1}) and endosulfan (1.2 l ha^{-1}) were applied during the first week of February 2002. In the middle of March, the rice was harvested manually.

Treatment NT(S). This treatment involved complete defoliation of pasture vegetation, fertilizer application, no-tillage seeding of soy bean followed by *Brachiaria brizantha* cultivation. The defoliation procedure was the same as adopted in treatment NT(A). Termophosphate (531 kg ha^{-1}) and KCl (130 kg ha^{-1}), equivalent to 85 and 21.3 kg per plot were applied in the middle of November 2001. Seeds of the precocious soybean variety 'Conquista' were inoculated with *Bradyrhizobium japonicum* in peat (250 g for 70 kg ha^{-1}) and seeded using 94 kg ha^{-1} (26

Figure 3. Five pasture reformations arranged in four blocks.

seeds m^{-1}). Sulfuramid was applied to combat ants both in this treatment and in treatment NT(R). The post-emergent herbicide bentazon (0.75 l ha^{-1}) and formicide fipronil were applied in early December 2001, while manganese sulphate (1.2 kg ha^{-1}) was applied as a foliar fertilizer at the beginning of January 2002. The same pesticides (chloropyrifos and endosulfan) as for treatment NT(R) were applied in early February 2002. In the middle of March, the soy bean was harvested manually. After harvesting, the plots with treatments NT(R) and NT(S), and in order to homogenize the experiment, the plots with treatments C, H, and T, were mowed.

We have evaluated many agronomic, environmental and economic parameters to quantify the consequence of the various reformation regimes, including:

(i) plant production, nutrient value and digestibility of forage;
(ii) distribution of the root system;
(iii) soil quality, aggregation, resistance to root penetration, stocks and fractions of carbon (C), nitrogen (N), phosphorus (P), cation exchange capacity, acidity, availability of nutrients and toxic elements, macro fauna and microbial biomass;
(iv) chemical analysis of soil solution;
(v) fluxes of trace gases, carbon dioxide (CO_2), nitrous oxide (N_2O) and nitric oxide (NO);
(vi) sequestration of C and N; and
(vii) economic viability.

Early results

The area of 3.2 ha selected to install the experiment has a homogeneous carbon and nitrogen content in the upper soil layer, as well as pH and texture, according to Andrade (personal communication, 2002).

Trace-gas measurements indicated that Treatment T increased the CO_2 emissions by 35% over the first 40 days, while herbicide application in the no-till treatments decreased CO_2 emissions by 20% over the first 30 days. Following establishment of the pasture grasses in the T and NT(R) treatments, CO_2 emissions were similar to C plots. Treatment T increased N_2O emissions 17-fold, but the highest emission rates (357 μg m^{-2} hr^{-1}) were measured after fertilizer application. A similar response was measured after fertilizer application in the NT(R) treatment. Tillage and fertilizer application resulted in increased NO emissions. Field measurements will continue to increase understanding of the long-term legacy of different reformation practices on soil gas-emission rates (Passianoto *et al*, 2003a,b).

Extractable N-NH_4^+ and N-NO_3^- concentrations increased dramatically in the T treatment seven days after tilling, while no change was observed in treatment C. N-NH_4^+ concentrations were almost always higher than N-NO_3^- concentrations in both treatments. An increase in NO_3^- concentrations after 18 days suggested an increase in the nitrification rate at that time. An increase in soil moisture seven days after ploughing may have improved conditions for microbial activity, increasing the mineralization of the soil organic matter. Higher NH_4^+ concentrations found in the tilled pasture could be a consequence of the slow transformation of NH_4^+ to NO_3^- and absence of plant uptake in these pastures. More than three weeks after tilling, increases in NH_4^+ (1.18 to 24.75 µg g^{-1} dry soil) and NO_3^- (0 to 14.83 µg g^{-1} dry soil) in the soil could lead to higher losses of the gaseous forms of N (N_2, NOx and N_2O), loss of N through leaching, as well as enhanced availability of this element for plant growth (Carmo *et al*, 2002).

Cassiolato (2002) evaluated the losses of dissolved organic carbon in the C and T treatments during the rainy season (January to April). The total dissolved organic carbon (DOC) concentration in the soil solution sampled at a depth of one metre and from the run-off was greater in treatment C (320 kg ha^{-1}) than in T (350 kg ha^{-1}). Since both treatments had the same DOC concentration in soil solution, the difference of 70 kg ha^{-1} corresponds to the C loss by run-off.

Soil microbial biomass C decreased after the second ploughing in treatment T, but increased in the long run after planting *Brachiaria brizantha*. Fertilizer application increased the microbial population in treatments NT(R) and NT(S). Herbicide temporarily inhibited microbial activity three days after application (Augusti *et al*, 2002).

A look to the future

Intensive agricultural activity in the Brazilian Amazon has increased in the last three decades. Since this land use is recent, the region is susceptible to an array of economic and social pressures. Pasture is the main land use in the Amazon region, because it represents one of the most inexpensive agricultural alternatives after deforestation and requires a relatively small and largely unskilled labour force.

Development activities, including new roads, electrical-power distribution, financial incentives and improvement of river transportation and ports, have made cleared land in the Amazon more valuable and promoted the trend of converting pastures to croplands. Nowadays, soybean cultivation, originally concentrated in the south-east and central parts of Brazil, has been extended through the Amazon region, especially in the states of Rondônia and Mato Grosso. The new road connecting Cuiabá to Santarém (BR-163) and improvements in the port infrastructure in Santarém and Porto Velho will reduce soybean exportation costs and will accelerate the cultivation of soybean on former pasture lands, and even promote the clearing of native vegetation, mainly from Cerrado vegetation for pasture cultivation.

Despite these increasing facilities for soybean cultivation, pasture will continue for some decades to be the most important land use in the Amazon region. Therefore, it is essential to continue promoting scientific research on pasture management and restoration as part of a sustainable-development strategy for the Amazon. The early findings presented here have begun to provide clues about the changes that are possible to control.

Acknowledgments

This work was supported by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP 00/02439-0 and 99/07103-0) and NASA. We thank João Arantes Jr, who kindly permitted us to work at Nova Vida ranch and assisted with logistical support. Gilmar Dri and Newton Almeida Soares from EMATER (Rondônia, Brazil) both provided valuable assistance. We also thank Dow Agroscience (São Paulo, Brazil) for field assistance.

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