Title: Land-Use Change, Soil Process and Trace Gas Fluxes in the Brazilian Amazon Basin

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We measured changes in key soil processes and the fluxes of CO_2, CH_4 and N_2O associated with the conversion of tropical rainforest to pasture in Rondônia, a state in the southwest Amazon that has experienced rapid deforestation, primarily for cattle ranching, since the late 1970s. These measurements provide a comprehensive quantitative picture of the nature of surface soil element stocks, C and nutrient dynamics, and trace gas fluxes between soils and the atmosphere during the entire sequence of land-use change from the initial cutting and burning of native forest, through planting and establishment of pasture grass and ending with very old continuously-pastured land.

All of our work is done in cooperation with Brazilian scientists at the Centro de Energia Nuclear na Agricultura (CENA) through an extant official bi-lateral agreement between the Marine Biological Laboratory and the University of São Paulo, CENA's parent institution.

The highlights of our results from the NASA-sponsored research project in Rondônia, Brazil include-

- **The measurement of substantial fluxes of N_2O from intact moist tropical forest, adding more evidence that tropical forests are a major source of N_2O in the global budget of this greenhouse gas.** We have also quantified a period of higher flux during the first two years after forest clearing for pasture, but the magnitude of the flux was less than has been measured in other tropical locations.

- **The confirmation that forest soils function as small but consistent consumers of atmospheric CH_4.** Pastures, in contrast, are net sources of CH_4 to the atmosphere. In the context of total accounting of CH_4 emissions from pasture establishment and operation, the soil fluxes account for only about 5%, while biomass burning and cattle emissions account for the rest.

- **The measurement of a consistently greater amount of N cycling in the soils of forests compared with pastures.** The magnitude of N cycling also decreases as pastures age. Nitrate production is important in both forest and pasture soils. These findings demonstrate a relatively open N cycle in forests and are consistent with declines in N fertility in older pastures.

- **The documentation of large losses of C during pasture conversion by biomass burning and subsequent decomposition of woody forest biomass.** Thirty-nine percent of C in forest biomass was lost immediately upon burning. Pools of woody biomass in older pastures indicate that the remaining C is lost over a period of less than 10 years.

- **The finding of small increases of surface soil C stocks in soils after forest conversion to pasture.** This pattern is caused by a rate of input of grass-derived soil organic matter that is greater than the rate of loss of soil organic matter that remains from the original forest.

We took three approaches to our biogeochemical studies: 1) frequent measurements during a complete annual cycle along two sequences that consisted of native forest and pastures cleared between 1989 and 1911 on a working cattle ranch; 2) less frequent measurements in a much more extensive area that included six additional sequences on a variety of soil types along a 700 km transect across Rondônia; and 3) intensive measurements of the biogeochemical changes that immediately follow forest clearing and pasture planting in a 3 ha plot on Nova Vida that we experimentally cut, burned and planted to pasture in a manner consistent with the way that large areas of forest are converted to pasture in Rondônia. Below we report the major findings from these three approaches.

A. Approach 1: Intensive Measurements Along Sequences of Forest and Pasture

This research was conducted at Fazenda Nova Vida, a 22,000 ha ranch in the municipality of Ariquemes (lat. 9 S, long. 34 W). Nova Vida is superbly suited for studies that examine the consequences of pasture creation because it contains forest reserves and pastures of a wide range of ages on similar soils under similar management. Its location along BR-364 and a good road network allow access throughout the year. We have a laboratory with line electricity and a dormitory on the ranch.

We identified two sequences of forest and pastures cleared at different times at Nova Vida on soils that are typical of Rondônia and the Amazon Basin as a whole. One sequence on kandiudults (red-yellow podzolic latossols) contained forest and pastures that were 3, 5, 9, 13, 20, 41 and 81 years old when we began measurements in 1992. The other sequence on slightly less clayey paleudults (red-yellow podzolics) contained a forest and pastures that were 3, 5 and 20 years old in 1992. All pastures were created from forest by clearing and burning and direct seeding of pasture grasses two to three months after slash burning. Pastures were not tilled or fertilized. The pastures cleared in 1951 and 1911 represent some of the oldest continuously-cleared land in Rondônia.

Soil Chemical Properties

Forest conversion to pasture had a large and predictable effect on the chemical properties of surface soil (Fig. 1). Soil pH increased by one to two units in three- to five-year-old pastures, but remained elevated above the pH of the original forest even in the oldest pastures. Exchangeable base cations of K, Ca and Mg and cation exchange capacity (CEC) followed a similar pattern. Moraes et al. (1996) describe these changes in detail. Acid-extractable P increased slightly in three-year-old pasture, but the change was lower in magnitude than the change in cations, and P returned to the level of the original forest in pastures aged five years and older (Fig. 1). Our preliminary information from the forest indicates that most soil P resides in fractions associated with Fe and Al phosphates and in organic P.

Soil Density, Carbon and Nitrogen Stocks

Pasture creation led to moderate increases in surface soil (0-10 cm) bulk density from 1.2 g cm^{-3} in the forest to 1.2 to 1.4 g cm^{-3} in pastures. Soil C and N concentrations in pastures were typically higher than in the original forest and soil C and N concentrations generally increased with pasture age. This led to higher soil C and N stocks in pasture soils (Fig. 1)

Soil Carbon Dynamics

We used the stable isotope ^{13}C to examine the pattern of loss of C in soil organic matter (SOM) derived from the original forest and the gains of C that result from incorporation of pasture-derived C in pasture soils. Forest-derived C in the pastures cleared in 1972 of both Nova Vida sequences represented 67 to 78% of the total C in SOM present to 30 cm in the original forest. The pasture cleared in 1911 contained 57% of the original forest organic matter. The increase of C in SOM derived from pasture grasses has been more rapid than the decline of forest-derived C. By modeling the rates of change of these two soil C pools, we estimated that approximately one-half to two-thirds of the C pool to 30 cm soil depth is stable over the 80-100 year time scale over which land-use change is likely to significantly alter total soil C pools. Pasture-derived C made up approximately 55% of the 0-30 cm total soil C stock after 20 years. Soil C turnover differed considerably in different SOM size fractions. Larger (200-2000μ) fractions of relatively undecomposed organic material became dominated by pasture-derived C in young pastures, while the smallest (<50μ) clay-associated fractions remained dominated by forest-derived material in older pastures. Changes to soil total C pools and the dynamics of soil forest-derived and pasture-derived pools are covered in a series of papers based on the research at Nova Vida (Feigl et al. 1995a, Moraes et al. 1996, Neill et al. 1997a,b, Bernoux and Cerri in press).

We have also used ^{13}C to examine how rapidly the C source for soil respiration shifts from forest-derived SOM to pasture-derived SOM. By measuring the ^{13}C in CO_2 respired from Nova Vida soil in laboratory microcosms (which includes only microbial respiration) and in the field (which includes microbial and root respired CO_2) we quantified the replacement of forest-derived C with pasture-derived C as a substrate for microbial respiration. While the bulk SOM (0-10 cm) in the pasture cleared in 1989 was 77% derived from forest, microbially respired soil C was 69% derived from pasture (Neill et al. 1996). When root respiration was included, pasture-derived C made up 70% of the total CO_2 emitted to the atmosphere from surface soil (Feigl et al. 1995b). Forest-derived C made up approximately 10% of total microbial respiration at 0-10 cm in 20-year-old pasture, but exhaustion of labile forest-derived C was complete after 81 years as pasture (Neill et al.1996). These studies point to the importance of new inputs of labile pasture-derived C for fueling soil microbial processes, including processes linked to trace gas production.

Soil Nitrogen Dynamics

We examined the effect of forest conversion to pasture on N cycling by measuring inorganic N pools and rates of net N mineralization and net nitrification over a seasonal cycle in the Nova Vida sequences (Neill et al. 1995). Soil extractable NH_4^+ and NO_3^- pools were similar in the surface soils (0-10 cm) of forest, but NH_4^+ dominated pasture inorganic N pools (Fig. 2). Rates of net N mineralization and net nitrification were higher during the wet season in both forest and pasture. Net mineralization and nitrification rates were consistently greater in forest soils than in pasture soils and rates generally decreased with pasture age (Fig. 3).

Because rates of net N mineralization are influenced by net N immobilization, net rates may not be an adequate measure of overall N cycling between organic matter and inorganic N pools. To examine the total amount of N mineralized from soils of forest and pastures of several different ages, we measured gross N mineralization rates using ^{15}N dilution on the same soils for which we collected net N mineralization rates. We found gross N mineralization rates were generally several times higher than net rates, especially when net rates were very low, but that the same pattern of higher N mineralization rates in forest compared with pastures also held for gross mineralization rates (Fig. 4). Both net and gross rates of N cycling indicate an overall decrease in N cycling rates as pastures age.

Trace Gas Dynamics--Methane

Our examination of CH_4 fluxes over an annual cycle showed that conversion of forest to pasture caused soils to switch from net consumers of CH_4 in forests to net producers of CH_4 in pastures (Steudler et al. 1996). Forest soils consumed CH_4 at all seasons of the year. Mean annual CH_4 consumption by forest soils was 470 mg C m^{-2} y^{-1}. Pasture soils consumed CH_4 for a brief period during the dry season but on average produced about 270 mg C m^{-2} y^{-1} for the year and production was similar across pasture ages. Methane fluxes from forest and pasture were closely correlated with soil water-filled pore space and the switch from CH_4 consumption to CH_4 production occurred at approximately 45% water filled pore space. Higher CH_4 fluxes from pasture soils were related to consistently greater water filled pore space above the 45% threshold, higher pasture soil pH and potentially greater inputs of labile C from pasture roots in surface soils. Compared with biomass burning and CH_4 production by cattle, the other principal sources of CH_4 to the atmosphere associated with forest clearing for pasture, fluxes from soils represent only approximately 5% of the CH_4 fluxes for the Brazilian Amazon. Our analysis suggests that conversion of forest to pasture in the Basin from 1975 through 1988 contributed between 12 and 14% of the global average rate of change in tropospheric CH_4 content for this time period (Steudler et al. 1996).

Trace Gas Dynamics--Nitrous Oxide

Fluxes of N_2O from soils measured over an annual cycle showed generally similar fluxes to the atmosphere from forests and pastures (Melillo et al. submitted). Nitrous oxide fluxes from the forest were in the range of 5 to 25 μg N m^{-2} hr^{-1} and were similar to fluxes measured from other tropical forests. The fluxes of N_2O from Nova Vida pastures, however, differed from the pattern of higher N_2O fluxes from young pastures found in other studies. Nitrous oxide fluxes from both forest and pasture soils were higher during the wet season. In the forest, soil N_2O fluxes were tightly correlated with soil water filled pore space and soil NH_4^+ pools. In the pastures, these relationships were weak. Fluxes of N_2O were not correlated with rates of net N mineralization or nitrification in either forest or pasture.

Trace Gas Dynamics--Carbon Dioxide

Fluxes of CO_2 from soils to the atmosphere were higher from pastures than from forests. In the dry season, CO_2 fluxes averaged 89 mg C m^{-2} hr^{-1} from forest and 111 to 158 mg C m^{-2} hr^{-1} from pastures (Feigl et al. 1995b). Over an annual cycle, this relative pattern was maintained, but wet season fluxes were two to three times higher than dry season fluxes (Steudler et al. submitted). Soil moisture was a good predictor of total soil CO_2 flux but soil temperature was not.

B. Approach 2: Extensive Measurements in a Transect Across Rondônia

We examined how forest conversion to pasture influenced soil stocks of C, N and P, rates of carbon and nitrogen cycling and trace gas emissions in six additional sequences across the state of Rondônia to test the generality of our findings from the intensive work at Fazenda Nova Vida. These six sequences encompassed both ultisols and oxisols, the two dominant soil orders in Rondônia and in the Amazon Basin. Soils spanned a range from sandy ultisols (13-16% clay) to clayey oxisols (67-75% clay). Each sequence contained a native forest and one or more pastures of different ages that were formed by cutting, burning and planting directly to pasture in the same manner used to create pastures at Nova Vida. We made measurements at a total of 10 pastures ranging in age from 3 to 20 years.

Soil Chemical Properties

Soil chemical characteristics following pasture creation generally followed the trends observed at Nova Vida (Neill et al. 1997a). Soil pH increased in young pastures, declined in older pastures, but remained elevated above level of the original forest in 20-year-old pastures. Cation exchange capacity and exchangeable base cations concentrations closely followed pH. Like the pattern at Nova Vida, soil acid-extractable P stocks increased in young pastures, but then declined, often to below the level in the original forest.

Soil Density, Carbon and Nitrogen Stocks

Conversion to pasture raised soil bulk density in six of the 10 pastures examined. Soil carbon stocks to 50 cm were greater than the original forest in eight of 10 pastures but significantly greater in only three cases (Neill et al. 1997a). Nitrogen stocks followed a similar pattern. Changes to soil C and N stocks were not clearly related to soil type or soil texture.

Soil Carbon Dynamics

We used ^{13}C abundance to partition the SOM in pastures into a biodegradable SOM pool that is susceptible to loss and an SOM pool that remains stable over time spans of several decades to 100 years. Between approximately one-fourth to one-half of soil C derived from the original forest vegetation was biodegradable and would potentially be lost to decay. In the majority of pastures examined, this C loss was more than balanced by inputs of C derived from newly planted pasture grasses (Neill et al. 1997a), a pattern consistent with the finding at Nova Vida.

Soil Nitrogen Dynamics

Patterns of soil inorganic N pools and cycling rates among forests and pastures across Rondônia were remarkably consistent with patterns measured at Nova Vida and appeared to be highly general across a range of soil types. Forest soils had higher inorganic N pools, higher rates of net N mineralization and higher rates of net nitrification than pasture soils (Neill et al 1997c). The consistently high proportion of mineralized N that is nitrified in the forests suggests that there is widespread potential for leaching and gaseous N losses from intact Amazon forest ecosystems.

Trace Gas Fluxes

Nitrous oxide emissions from forest soils throughout Rondônia ranged from 17 to 34 ug N_2O-N m^{-2} hr^{-1} and were similar to the fluxes measured at Nova Vida. Emissions from pasture soils were comparable to or less than the emissions from forest soils except for one 12-year-old pasture in the high clay oxisol at Vilhena, which had a flux that was more than double that from the corresponding forest stand. All forest soils consumed atmospheric CH_4. Consumption rates were similar to those measured at Nova Vida, except for the forest stand in Vilhena, which had the highest CH_4 uptake rate 0.12 mg CH_4-C m^{-2} hr^{-1}) we have measured in Rondônia. The pastures throughout Rondônia showed net CH_4 emission. The highest CH_4 emissions measured (up to 0.28 mg CH_4-C m^{-2} hr^{-1}) were from two pastures in Vilhena.

Approach 3: Intensive Measurements During Forest Cutting, Burning and Planting to Pasture

To study the dynamics of soil carbon and nitrogen cycling and trace gas fluxes that occur during the early stages of pasture creation not represented in our sequences at Nova Vida, we cut, burned and planted pasture grasses in a 3 ha plot of forest directly adjacent to the reference forest of Sequence I at Nova Vida. The forest was cut with chain saws at the beginning of the dry season in June, 1994. The slash was burned in September, grass (*Brachiaria brizantha*) was planted in January, during the middle of the rainy season, and a dense grass cover was established by February. This clearing sequence paralleled the sequence used to create other pastures at Nova Vida. Forest biomass and chemical composition of biomass compartments and size fractions were measured before and after the burn to determine combustion losses of C and nutrients. Carbon and nitrogen cycling and trace gas fluxes were monitored in the experimental plot before cutting through burning and grass establishment. Measurements were compared at each stage with measurements in the adjacent intact forest.

Forest Biomass and Combustion Losses

Total forest aboveground biomass was 299 t ha^{-1} (141 t C ha^{-1}). This is comparable to biomass in the few other forests in Rondônia where it has been measured. Biomass losses during burning totaled 39%. Losses were highest in leaves and twigs < 5 cm diameter (92%), lower in larger (5-10 cm) branches (40%) and lowest in large (>10 cm) trunks (22%). Biomass samples before and after the burn are currently being analyzed to permit calculations of element losses (P. M. da Graça, 1997).

Soil Chemical Properties

Soil pH before cutting averaged 4.55 at 0-5 cm and 4.50 at 5-10 cm. Two days after burning, pH at 0-5 cm rose to 5.24, while pH at 5-10 cm remained unchanged at 4.48. Six weeks following the burn, pH had risen to 6.78 at 0-5 cm and 5.74 at 5-10 cm. Analysis of soil samples collected post-burn for exchangeable aluminum and base cation content is in progress.

Soil Density, Carbon and Nitrogen Stocks

Cutting and burning did not change soil bulk density. Mean densities at 0-5 cm were 1.08 ± 0.04 g cm^{-3} before cutting, 1.05 ± 0.03 g cm^{-3} one day pre-burn and 1.07 ± 0.04 three days post-burn. These data suggest that changes to soil density during pasture establishment are likely more related to introduction of grass and cattle than any direct physical changes caused by vegetation removal and burning. Cutting and burning were similarly not associated with immediate changes to soil C stocks. These data combined with information on pasture soil C stocks from the sequence at Nova Vida indicate that long-term gradual increases to soil C and N stocks are linked more closely to establishment of pasture grasses than to any C inputs caused by cutting and burning.

Soil Carbon Dynamics

Forest cutting had a large but apparently relatively short-lived effect on soil microbial biomass C in the top 10 cm. Before the forest was cut, microbial biomass was approximately 243 μg C g^{-1} dry soil. Three months after cutting, but before the slash was burned, microbial biomass C increased to 350 μg C g^{-1} dry soil. Burning had no immediate effect, but by three months after the burn, microbial biomass C increased again to 575 μgC g^{-1} dry soil. Eight months after the burn, microbial biomass C declined to less than 300 μgC g^{-1} dry soil, approximately the level in the reference forest. We are currently analyzing soil samples for ^{13}C that will allow us to quantify inputs of grass-derived C in the months immediately after the burn. We think these inputs are important, not only for controlling microbial biomass and soil respiration, but perhaps for fueling N_2O emissions as well.

Soil Nitrogen Dynamics

We expected soil inorganic N pools and cycling rates to be much more dynamic during the cut and burn sequence than total soil C or N stocks. As a result, we measured soil extractable NH_4^+ and NO_3^- pools, laboratory potential net mineralization rates and potential net nitrification rates at closely-spaced intervals of days to weeks during the entire cutting and burning sequence. Pools of both NH_4^+ and NO_3^- increased in response to cutting (Fig 2). The increase in NO_3^- pools was more rapid and of greater magnitude than the increase in the NH_4^+ pool (Fig. 2). The peak NO_3^- pool occurred immediately before the burn, while the peak NH_4^+ pool occurred several days after the burn.

Burning itself did not appear to change dramatically either NO_3^- or NH_4^+ pools. Rather, the elimination of vegetation and plant demand for inorganic N resulted in large increases in soil N pools. This effect was greatest for NO_3^- pools, which peaked at more than five times their levels in the adjacent reference forest. NH_4^+ pools peaked at two to three times their level in the reference forest, but peak NH_4^+ pools after the burn were only slightly higher than the typical dry season elevated NH_4^+ pool (Fig. 2). When compared with soil inorganic N pools in pastures in the sequence at Nova Vida, NH_4^+ pools during the cut and burn sequence were similar in magnitude and timing to the seasonal swings in inorganic N pools that occur in pasture soils (Fig. 4). In contrast, the changes in NO_3^- pools during the cut and burn sequence were two- to three-fold greater than the normal seasonal cycle in the forest and vastly greater than the NO_3^- pools in pastures, which are typically very low (Fig. 2).

The period of largest change in inorganic N pools occurred within four months of forest cutting. By November, which corresponds to the beginning of the first rainy season following clearing, pools had declined by approximately half from their peak, but were still two to three times greater than pools in the reference forest or typical early rainy season forest inorganic N pools. The duration that pools stay elevated is not known, but it likely plays a very important role in mediating total N losses through the first year or two following clearing and pasture establishment.

Rates of net N mineralization and net nitrification through the cutting and burning cycle, in contrast to inorganic N pools, remained very similar to rates in the reference forest (Fig. 3). We interpret this pattern to indicate that microbial processing of organic matter remained relatively constant over the cut and burn sequence but that the products of mineralization and nitrification accumulated when plant uptake was eliminated. Large inputs of organic material that reached the soil surface after cutting did not stimulate microbial release of N in surface soils, likely because this deposition occurred during June through August at the height of the dry season. By four months after forest cutting, rates of net N mineralization and net nitrification still more closely resembled rates in the reference forest than rates in established pastures at Nova Vida.

We measured the rate of gross N mineralization at several points during the cutting and burning sequence to examine changes in the mineralization/immobilization relationship that would help in interpreting patterns of net N mineralization. Before cutting, gross N mineralization rates in the forest were approximately three times net rates (Neill et al. submitted). Between cutting and burning and immediately after burning, gross and net N mineralization rates were similar. One month after burning, the gross N mineralization rate was much higher than the net N mineralization rate, probably because there was high net N immobilization as a result of high post-burn C availability. As with the net N mineralization rates, we did not detect a pronounced increase in gross N mineralization rate following cutting or burning.

Trace Gas Fluxes

The dynamics immediately after forest cutting and burning are also critical for understanding the net trace gas fluxes caused by land-use transformation. A significant portion of the total trace gas flux after deforestation could occur in a relatively short period if flux rates are greatly elevated. In the new pasture at Nova Vida, N_2O emissions increased by more than two times following cutting (Melillo et al. submitted). Fluxes continued to be elevated through the dry season until slash burning. Burning increased N_2O emissions to more than double the pre-burn rate and to more than six times the rate in the reference forest. Nitrous oxide emissions declined in the months following the burn, but after grass establishment in January, emissions increased steadily over the next nine months and reached a level three times the forest stand.

The effects of cutting and burning for pasture creation on the fluxes of CH_4 were nearly as dramatic as observed for N_2O but were of shorter duration. Immediately after forest cutting, soil CH_4 consumption decreased by 4.5 times. Soil CH_4 consumption continued to be reduced at least two fold through the burn and immediate post-burn period. Within one month after grass was established in the new pasture, CH_4 consumption returned to rates that were similar to the forest. Rates remained at this level for the next eight months.

Pasture creation did not have a dramatic effect on soil respiration. Forest cutting did not substantially alter soil respiration rates, but burning increased the rates by about 25% compared with the reference forest. Soil respiration rates declined by about 20 % one month after the burn but increased steadily after grass establishment to a level about 25% greater than the reference forest at nine months after burning.

Education and Training

Three Ph.D. dissertations and one Masters thesis at CENA-USP have also been completed with NASA support.

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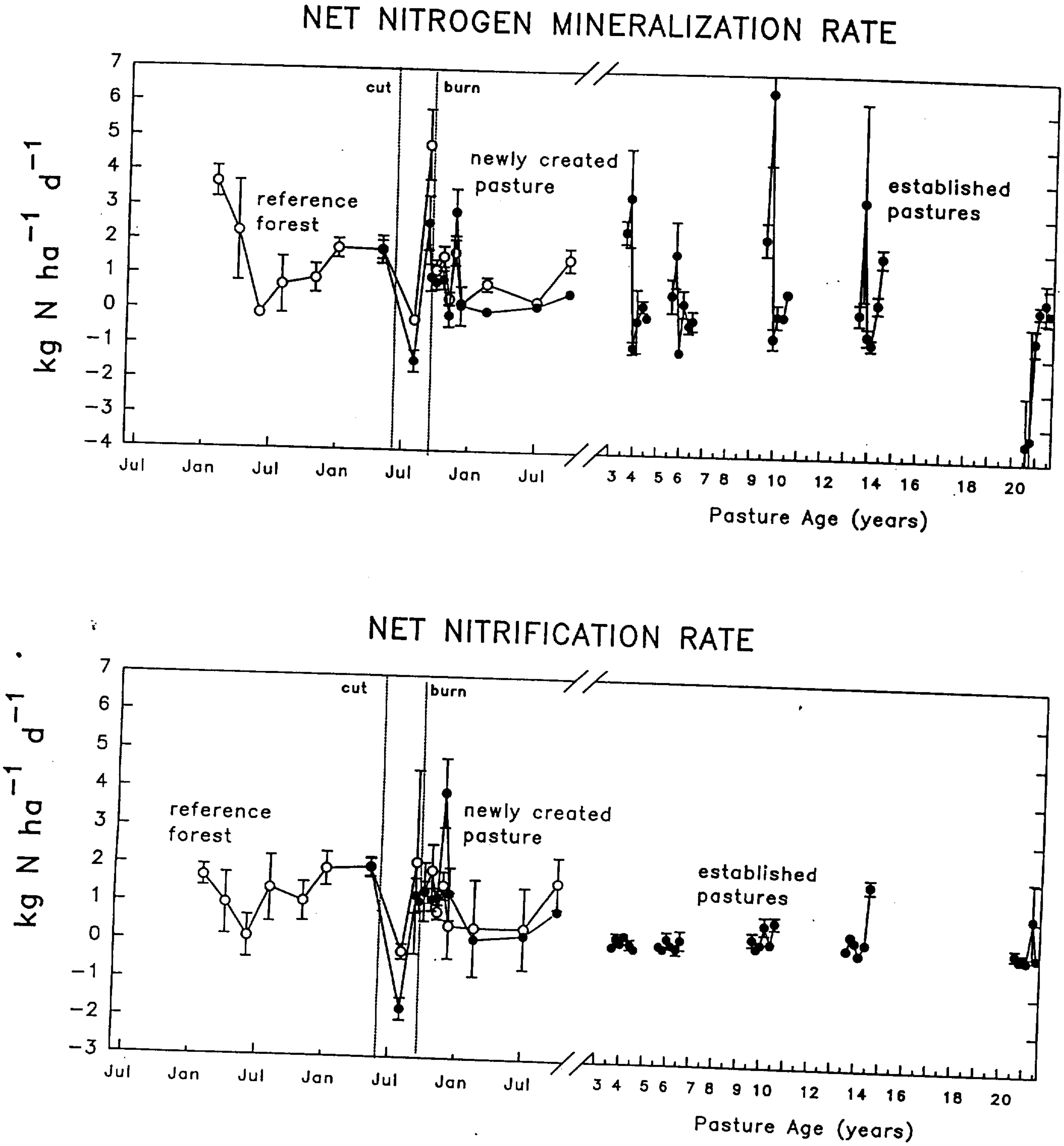

Fig. 3a,b. Rates of net N mineralization and net nitrification in surface soil (0-10 cm) in a reference forest and in a newly created pasture at Nova Vida. Unlike NH_4^+ and NO_3^- pools, rates of net N mineralization and net nitrification did not change greatly during the curring and burning of pasture creation.

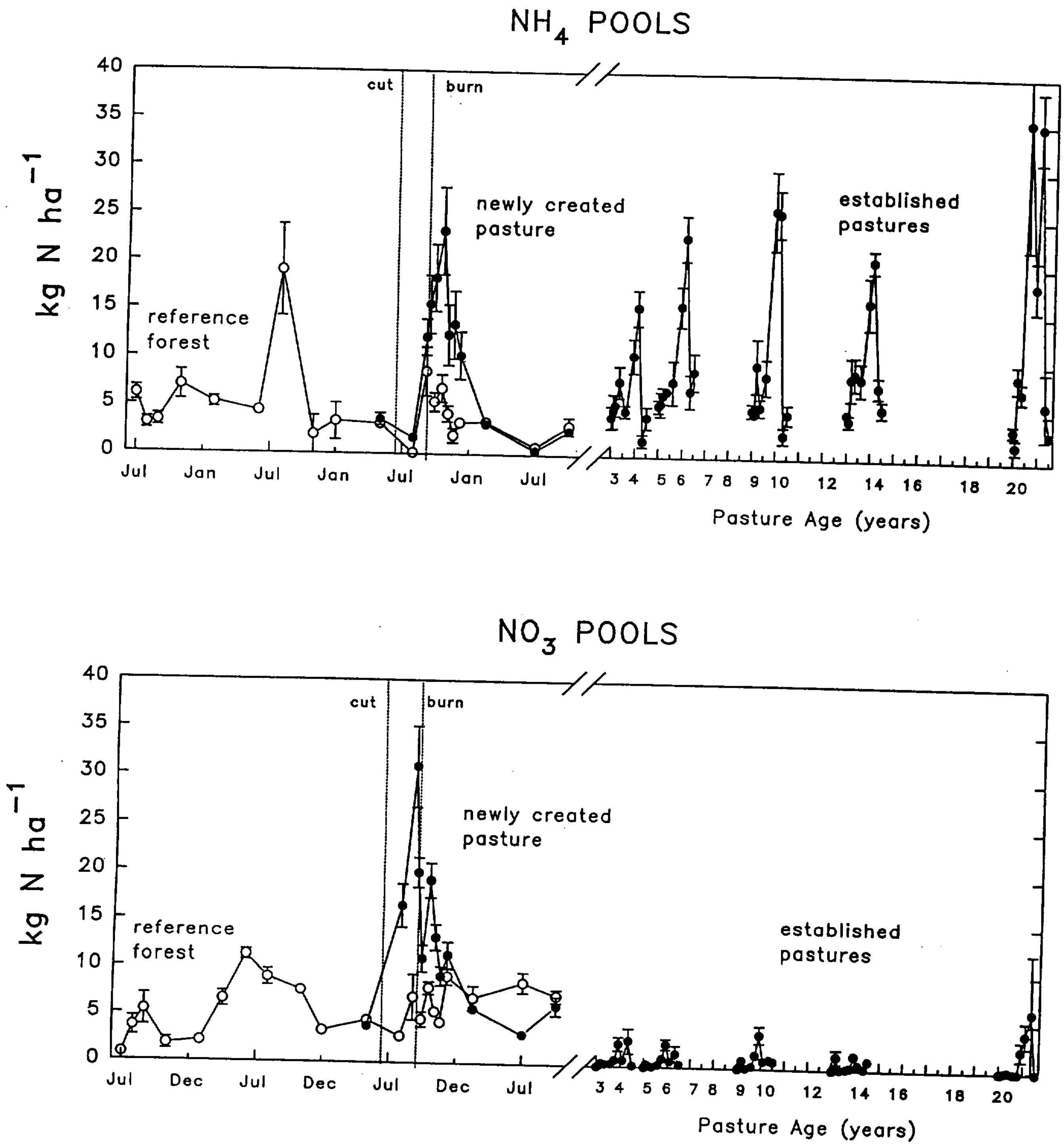

Fig. 2a,b. Soil NH_4^+ and NO_3^- pools in surface soil (0-10 cm) in a reference forest and in a newly created pasture at Nova Vida. The new pasture was formed from cutting and burning an area of forest directly adjacent to the reference forest. NH_4^+ and NO_3^- pools in established pastures are from the Nova Vida chronosequence. Soil NH_4^+ pools in the new pasture increased compared with the reference forest during first 6 months after cutting, but the NH_4^+ pool during this stage was comparable to NH_4^+ pools in established pastures. Soil NO_3^- pools also increased compared with the reference forest during the first 6months after cutting and NO_3^- pools 9 months after burning were still more than 2 times pools in established pastures.

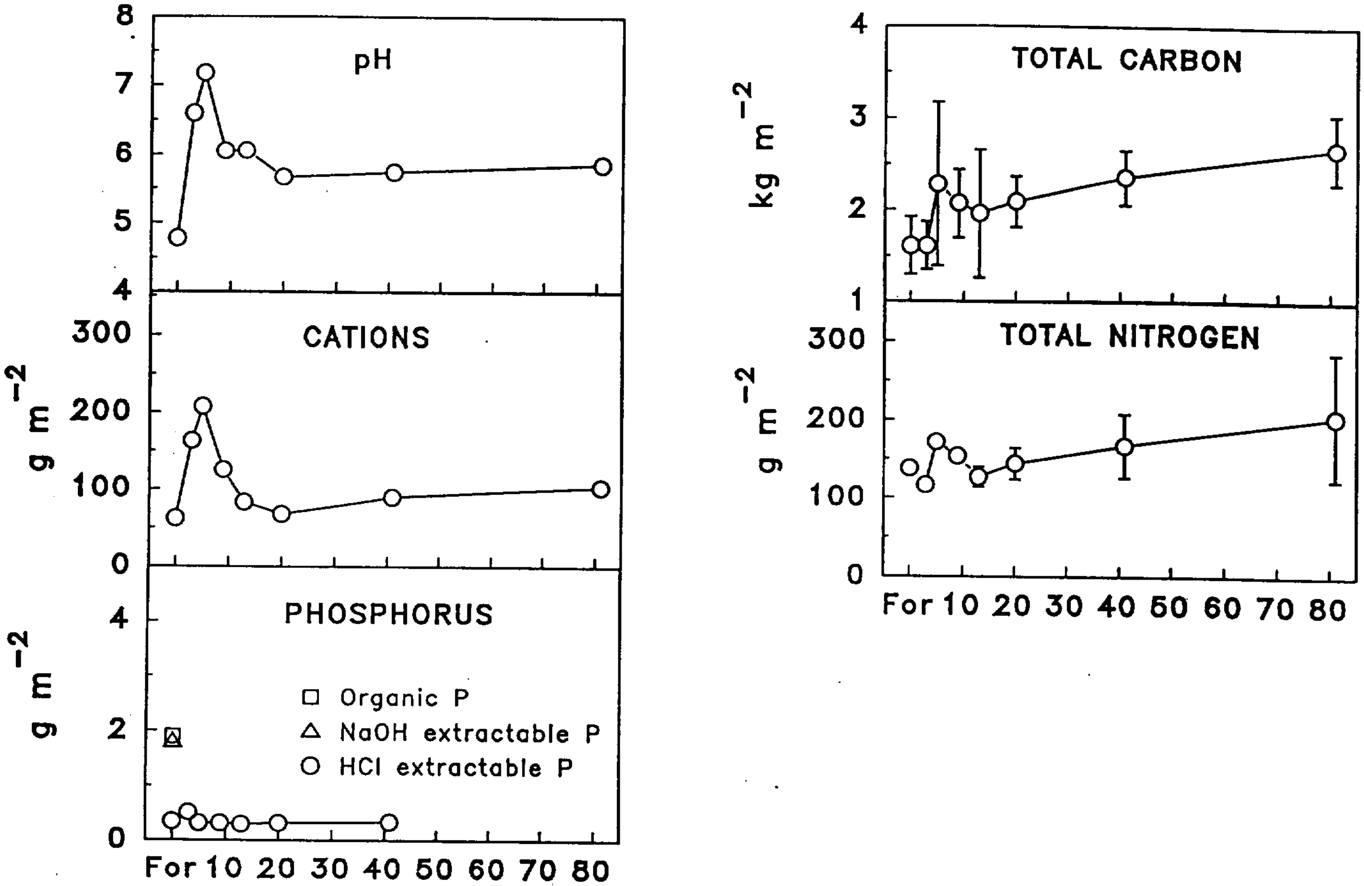

Fig. 1 Changes to soil pH, cation stocks, phosphorus stocks, total carbon and total nitrogen stocks in surface soil (0-10 cm) along a chronosequence consisting of forest and pastures ranging in age from 3 to 81 years at Fazenda Nova Vida, Rondônia. Soil pH (1:2.5 in H2O) peaked in 5-year-old pasture but then remained elevated after 81 years. Cation stocks (sum of K, Ca, Mg and Na) also peaked in 5-year-old pasture but after 20 years in pasture returned to the level of the original forest. Stocks primary mineral P (HCl extractable P) were very low and showed only a slight increase in 3-year-old pasture. Preliminary measurements of stocks of organic phosphorus and phosphorus associated with amorphous and crystalline Al and Fe hydroxides (NaOH extractable P) in the forest indicate that these forms make up the largest components of total P, but how they change during pasture aging in not known. Total carbon and nitrogen stocks increased with pasture age. Error bars for total C and total N are ± 1 standard deviation.