ECONOMIC AND ENVIRONMENTAL SUSTAINABILITY TRADE-OFFS IN CATTLE FARMING: APPLICATION TO TROPICAL COSTA RICA

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ABSTRACT

Sustainability of tropical pastures has economic and environmental dimensions and is affected by pasture species, age and management. Using a systems-based approach, the sustainability of beef cattle systems was analyzed in terms of economic viability, soil nitrogen stock change, CO_2 loss/sequestration, N_2O and NO emissions, pollution by herbicides and nitrogen leaching loss, for a case study in the Northern Atlantic Zone of Costa Rica. Development scenarios were explored for the next 25 years based on degradation of current naturalized pastures and on possible introduction of grass-legumes and fertilized improved grasses. With degrading pastures, economic profit, soil nitrogen stock, nitrogen leaching and N_2O and NO emissions are simulated to decrease in time, and CO_2 loss and herbicide use to increase. With the introduction of alternative pastures, the reverse will happen. The replacement of degrading naturalized pastures with grass-legumes or fertilized grasses is calculated to lead to a net sequestration of CO_2 of up to 50

t C ha^{-1}. Policy makers and stakeholders concerned with land use should realize the often conflicting nature of the various dimensions of sustainability.

INTRODUCTION

Since the beginning of this century, large tracts of forests in the humid tropics of Latin America have been cleared and converted into pastures for beef cattle ranching (Hecht, 1992; Kaimowitz, 1996). In the Northern Atlantic Zone (NAZ) of Costa Rica (Figure 1), deforestation started in the late 19th century and some 40% of the total area of 450,000 ha is estimated to be currently under pasture for beef cattle ranching (Veldkamp et al., 1992; Bouman et al., 1998a). Typically for the humid tropics, pastures are dominated by relatively unproductive naturalized and native grass species, and management is characterized by low levels of external inputs and zero fertilizer use (Hernandez et al., 1995). The conversion of forest to pasture has effects on various dimensions of economic and environmental sustainability, such as income, environmental pollution with pesticides, trace and greenhouse gas fluxes and soil degradation. Immediately after forest clearing, soils are relatively rich in nutrients (Veldkamp, 1993), leading to relatively high yields and consequently high farmers' incomes. Invading weeds are combated by a combination of manual weeding and herbicides, the latter introducing toxic substances into the ecosystem. Detwiler & Hall (1988) estimated that the annual net emission of carbon (C) in the form of the greenhouse gas CO_2 by tropical deforestation may be 0.4-1.6 10^9 t C, or only second to the global C release from burning of fossil energy (about 5.3 10^9 t C y^{-1}). For Latin America, Houghton (1991) estimated the total net release of C between 1850 and 1985 due to changes in land use at about 30 10^9 t, mainly caused by the increase in area under pasture. For another greenhouse gas, nitrous oxide (N_2O), Luizão et al. (1989) found that forest to pasture conversion in the Central Amazon led to a threefold increase of the soil emission levels. For the NAZ of Costa Rica, Keller et al. (1993) reported that soils from recently established pastures emitted an order of magnitude more N_2O than did forest soils. A similar trend was found for nitric oxide (NO), which is a precursor to the formation of tropospheric ozone, yet another greenhouse gas.

With continued pasture use, economic and environmental sustainability may change. When stocking rates are adapted to the carrying capacity of the environment - as determined by climate, soil properties and natural nutrient inputs - pasture production levels can be sustained for long periods of time and farmers' income maintained. However, when stocking rates are too high, the removal of nutrients (especially nitrogen, N) via cattle products and via leaching, volatilization and denitrification may be higher than the inputs, and soils are 'mined' (Haynes & Williams, 1993). This results, in the long run, in pasture degradation as evidenced by productivity decline and weed invasion (Myers & Robbins, 1991; Williams and Chartres, 1991). 't Mannetje and Ibrahim (as quoted in Jansen et al., 1997) estimated that over 70% of the pastures in the NAZ are in an advanced stage of degradation, with overgrazing and lack of sufficient N input identified as principal causes by Hernandez et al. (1995). Values of annual soil N depletion rates in tropical pastures have been reported to be as high as 65-94 kg ha^{-1} (Cadisch et al., 1994; Thomas et al., 1992). With decreasing soil fertility, weeds and undesired grass species compete heavier for light and nutrients, and more herbicides (and manual labour) are needed to control them (Myers & Robbins, 1991). On the other hand, aging and degradation of pastures can also have beneficial effects on sustainability indicators. For example, Keller et al. (1993) reported that, after a decade following forest clearing, N_2O and NO emissions from pastures in the NAZ dropped below original forest levels. Finally, with decreasing pasture yields, farmer's income declines (Bouman et al., 1998c) and degraded pastures may eventually be abandoned because of non-profitability (Uhl et al., 1988; Haynes & Williams, 1993).

Significant research efforts are undertaken to halt pasture degradation, mostly focusing on the use of grass-legume mixtures and fertilized improved grass species (Ibrahim, 1994; Hernandez *et al.*, 1995; Miller & Stockwell, 1991; Teitzel *et al.*, 1991). These alternative technologies, however, also have implications for the various dimensions of sustainability. First of all, economic viability is a prerequisite for adoption by farmers (Jansen et al., 1997). Most of the new technologies halt soil N mining by supplying extra N input via fixation by micro-organisms in symbiosis with legumes or directly via fertilizers. Improved grass species have been reported to produce a relatively high amount of deep root biomass with a low turnover time, thus acting as a sink for CO_2 (Veldkamp, 1993; Fisher et al., 1994; van Dam et al., 1998). On the other hand, recent measurements on fertilized pastures in the NAZ indicated high emissions of N_2O and NO relative to unfertilized naturalized pastures (Veldkamp et al., 1998). Finally, the use of fertilizer potentially contaminates soil and surface water via N leaching.

Various dimensions of sustainability thus surround tropical pasture ecosystems and are affected – sometimes in opposite directions – by pasture type, age and management. Policy makers concerned with land use increasingly are aware of the various dimensions of sustainability and need quantitative information on sustainability parameters. An integrated approach is needed that assesses trade-offs among the various dimensions of sustainability. The aim of this paper is to quantify these sustainability dimensions for current degrading and alternative non-degrading pastures in the NAZ of Costa Rica: economic viability, soil N balance, CO_2, N_2O and NO emissions, pesticide use and N leaching loss. The magnitude of these sustainability dimensions is explored for likely development scenarios in the beef cattle sector for the coming 25 years. The methodology employed is based in integrated system-analysis and considers all aspects of a beef production system (pastures, herds and feed supplements). Tools used include an expert system, dynamic simulation modelling and linear programming techniques.

METHODOLOGY

Framework

A beef cattle system consists of three components: (*i*) the herd, generating the marketable product and characterized by feed requirements, (*ii*) pastures supplying feed and characterized by sustainability indicators, and (*iii*) feed supplements. An expert system called PASTOR (PASture and livestock Technical coefficient generatOR; Bouman et al., 1998b; Bouman & Nieuwenhuyse, 1998) was used to compute input and output technical coefficients for a number of alternatives for each of these components. Alternatives were based on production levels and management technology. Examples of general technical coefficients are costs and labour use. For herds, additional technical coefficients are the amount of meat produced and feed requirements expressed as crude protein and metabolizable energy. For pastures and feed supplements, additional technical coefficients are crude protein and metabolizable energy delivery. PASTOR was first extended to compute sustainability indicators for the alternative pastures. Next, a linear programming (LP) model was used to quantify the economic viability of the whole beef production system. The LP model maximizes economic surplus by combining selected alternatives from each of the three subsystems based on their technical coefficients. Effects on sustainability parameters are a consequence of the selected pastures. Alternative development scenarios in the NAZ were explored by running the LP model with different pasture options.

PASTOR

A pasture is defined by a combination of species, soil type and management. Species can include native and naturalized grasses, grass-legume mixtures and improved varieties. Management variables are stocking rate, fertilizer application rate and herbicide use. Stocking rate is explicitly taken into account because of its effect on pasture production and on the soil N balance (Ibrahim, 1994; Hernandez et al, 1995). Technical coefficients are generated using a 'target oriented approach' (Van Ittersum & Rabbinge, 1997): target production levels are predefined and used by PASTOR to calculate required inputs. Target pasture production levels may vary from potential production under non-limiting situations, via close-to-actual situations to extremely low levels on mined soils. In the first case, high levels of external inputs (e.g. fertilizers, crop protection) are required, and in the latter case, low levels of external inputs suffice. For non-mining pastures, the amount of fertilizer input is calculated under the boundary condition that the soil N balance be zero. Alternatively, there is an option to use PASTOR descriptively: all inputs and outputs are user-defined and, instead of fertilizer input, PASTOR will calculate the resulting soil N balance. In addition to target production levels, PASTOR specifies the technology used to realize these. For example, weeding may be performed chemically, manually or using a combination of both. The technology used affects costs, labour requirements and sustainability indicators. Costs and labour use involve material inputs such as fences, tools and herbicides, and operations such as establishment, fertilizer application and weeding.

For herds, PASTOR computes animal composition, production and feed requirements from specifications of animal growth rates, calving interval, mortality rate and buying/selling strategy. The generated herds are stationary, implying that there are no dynamics in neither herd size nor composition over the year(s) (Upton, 1989; Hengsdijk et al., 1996). The calculation of feed requirements is based on NRC equations (1989, 1996). Costs and labour use for herds involve construction, buying and maintenance of corrals, feed troughs, various equipment, vaccinations, assistance at birth and animal health care. For feed supplements, PASTOR calculates the amount of metabolizable energy and crude protein, and costs and labour use for purchase and on-farm delivery.

PASTOR was parameterized for pastures and herds in the NAZ using data from surveys, field experiments and literature (van Loon, 1997; Bouman et al., 1998b), and was carefully reviewed by a number of external experts.

Soil nitrogen balance and leaching loss

The soil N balance is calculated using an adapted version of NUTMON (Stoorvogel, 1993). This model is a book-keeping method of all inputs, namely atmospheric deposition, fixation by micro-organisms, manure and urine (from the grazing stock), fertilizer, and all outputs, namely the amount that is removed by grazing and losses by leaching, volatilization and denitrification/nitrification. A negative balance indicates that the soil is being mined.

Trace and greenhouse gasses

Emissions of CO_2, N_2O and NO from pastures were calculated using the simulation model DNDC (DeNitrification-DeComposition; Li et al., 1992). DNDC is an integrated one-dimensional model of field-level C and N dynamics in soil-vegetation systems, with a strong focus on denitrification and N oxide emissions. Simulation results were found to match observed dynamics of soil organic carbon (SOC) and emission of N_2O and NO from naturalized pastures after forest clearing in the NAZ (Plant, 1998), Figure 2. Plant & Bouman (1998), linking PASTOR and DNDC to simulate SOC levels and N_2O and NO emissions of grass-legume mixtures and fertilized improved grasslands, were able to reproduce measured N_2O and NO emissions in the NAZ quite well. Simulated N_2O and NO emission rates reached stable levels about 25 years after pasture establishment, which is the time frame used in this study. Therefore, the 25-year N_2O and NO emission rates were used here as a sustainability measure.

The main contribution of pasture-ecosystems to atmospheric CO_2 concentration stems from changes in soil organic carbon when forest is converted into pasture (Veldkamp, 1993). Therefore, the difference in SOC under forest and under pasture 25 years after establishment was used as a CO_2 sustainability measure.

Pesticide use

The sustainability effect of pesticides was quantified in the Pesticide Environmental Impact Index (PEII) as developed by Jansen et al. (1995). The PEII takes into account the amount of active ingredients in the pesticide, their degree of toxicity and their persistence in the environment:

$$PEII = \sum_{a=1}^{n} \sum_{b=1}^{m} A_{a,b} AI_b TOX_b DUR_b$$

Where n,a = total and a^{th} number of pesticide application; m,b = total number and b^{th} type of active ingredient in pesticide; A = amount of pesticide; AI = fraction active ingredient in pesticide; TOX = indication of toxicity of active ingredient; DUR = indication of duration of existence of active ingredient, taken as the square root of the duration in days. TOX for pesticides in the NAZ was derived from the WHO toxicity code (Castillo et al., 1995): WHO code = Ia, TOX = 9; WHO code = Ib, TOX = 7; WHO code = II, TOX = 5; WHO code = III, TOX = 3; WHO code = V, TOX = 1.

The only pesticides applied in pastures in the NAZ are herbicides (Van Loon, 1997). PASTOR calculates the amount applied per hectare as a function of above-ground biomass by interpolation between a relatively low amount applied at maximum biomass level and a relatively high amount applied at minimum biomass level. The reasoning is that the 'weed-suppressing' capacity of the (desired) grass species increases with its ground-cover, and that ground-cover and biomass are positively related.

Economic sustainability: LP modelling

The LP model maximizes economic surplus and selects for a certain soil unit, the herd size, type of pasture, stocking rate and type and amount of feed supplements by. Economic surplus is defined as the value of meat production minus all costs of inputs and labour. A feed balance guarantees that the feed requirements of the animals are met by a combination of pasture and supplementary feed. An animal number balance equates the total number of animals in the herd to the area of pastures selected times the selected stocking rates on these pastures. A soil use balance restricts the area of selected pastures to the total soil area available. Labour is supposed to be available in unlimited supply at a fixed wage rate. More details and the equations of the model are presented in Bouman and Nieuwenhuyse (1998).

APPLICATION

Site description

The NAZ is in the Northeastern part of Costa Rica, between 10°00' and 11°00' latitude and 83°00' and 84°00' longitude (Figure 1). It has a mean daily temperature of 26 °C (± 2°C), mean annual rainfall of 3500-5500 mm, and an average relative humidity of 85-90%. Soils have been described by Wielemaker and Vogel (1993) and Nieuwenhuyse (1996). Most of the soils suitable for agriculture are fertile and well drained, and were classified as SFW (covering 37% of the area). About 77% of the pastures are dominated by relatively unproductive naturalized and native grasses, such as *Ischaemum ciliare*, *Axonopus compressus* and *Paspalum* spp (Hernandez et al., 1995), henceforward called 'Natural'. Current Natural pasture production varies from 15 t DM ha^{-1} y^{-1} on relatively fertile soils brought recently under cultivation, to 8-10 t DM ha^{-1} y^{-1} on soils already in use for longer periods of time (Veldkamp, 1993; own data and various unpublished measurements). Beef cattle breeding and fattening farms account for about 66% of the total herd in the NAZ, with mean stocking rates of 1.4-1.9 animal units (AU; 1 AU = 400 kg liveweight) ha^{-1} (Van Loon, 1997). Herbicides used are Tordon-101, containing Picloran, 2.4.D and Combo, containing Picloran and Metasulfuran. Alternative pastures being introduced in the area are the improved variety *Brachiaria brizantha* and the grass-legume mixture *Brachiaria brizantha-Arachis pintoi* (Ibrahim, 1994; Hernandez et al., 1995). On *B.brizantha*, Tordon-101, 2.4.D and Combo are applied, and on *B.brizantha-A.pintoi*, weeds are controlled strictly manually to avoid killing the legume.

Generated pastures and herds

PASTOR was used to generate technical coefficients of a number of alternatives for three pasture systems (Table 1):

1. Natural. No fertilizer is applied and soil mining takes place. Stocking rates range from 1 to 4 AU ha^{-1}, in steps of 0.1 thus resulting in 31 alternatives. Total above-ground production levels are 15, 10 and 5 t DM ha^{-1}, representing the effect of productivity decline due to soil degradation in time: the 15 ton level is estimated to be the production level shortly after forest clearing; the 10 ton level is representative for mean current production levels; and the 5 ton level is estimated to be the minimum production level when soils are mined for a number of years (Bouman et al., 1998c).
2. Grass-legume. A mixture of *B.brizantha* with *A.pintoi*. Since the legume supplies N to the pasture via microbial fixation (estimated at 150 kg ha^{-1}; Ibrahim, 1994), the soil N balance is zero and no fertilizer is applied. Stocking rates range from 1 to 3 AU ha^{-1}, in steps of 0.1, resulting in 21 alternatives. At stocking rates higher than 3 AU ha^{-1}, the grass-legume mixture was proven to be unstable (Ibrahim, pers. comm.).
3. Brachiaria. Fertilized *B.brizantha*. The soil N balance was zero by fertilizer-N applications ranging from 0 (resulting in the lowest production level) to 100% of the amount needed to realize maximum production. As result of the different amounts of fertilizer, pasture production varied between 6 to 34 t DM ha^{-1}. Stocking rates varied from 1 to 6 AU ha, in steps of 0.1. The combination of fertilizer application rates with stocking rates resulted in 819 alternatives.

Soil parameters for the soil N balance were taken from own measurements and literature (Cadisch et al., 1994; Haynes & Williams, 1993; Nieuwenhuyse, 1996; Stoorvogel, 1993; 1995), Table 2. High amounts of (intensive) rainfall coupled with high permeabilities and macropore flows of the soils in the NAZ (Nieuwenhuyse, 1996) result in relatively high N losses (Cadisch et al., 1994; Haynes & Williams, 1993; Whitehead, 1995). Recovery of N from faeces is low because of 'preferential deposition' in the field: leaching and other losses are highly concentrated in preferred dung-deposition areas close to corrals, under shade trees and at river banks (Haynes and Williams, 1993; Thomas et al., 1992).

Separate breeding and fattening herd types were generated. In the breeding system, calves are bred and subsequently sold at a certain age or live weight. No animals are bought externally. In the fattening system, young animals are bought, fattened for a period of time, and then sold. No animals are bred internally. Main input characteristics and generated technical coefficients are given in Table 3. The LP model was solved for the two herd types separately, for unit areas of 100 ha SFW soil, offering Natural with a production of 15 t DM ha^{-1}, Natural with 10 t DM ha^{-1}, Natural with 5 t DM ha^{-1}, Grass-legume and the Brachiaria options. Feed supplements offered were green rejected bananas, a chicken-dung based concentrate and a P mineral salt (Van Loon, 1997). To account for fluctuations in beef prices, the model was solved with mean 1996 prices, representing relatively low values, and mean 1997 prices, representing relatively high values (Table 4). Prices were derived from local cattle auction and slaughter house data. All investments were expressed as annuities using a discount rate of 7%.

RESULTS

Sustainability trade-offs

The trade-off among sustainability indicators of pastures is illustrated in Figures 3 and 4. In the figures, 'Yield' is the amount of above-ground biomass that is eaten and subsequently removed by the cattle, equivalent to about 50% of total above-ground production. For Natural and Grass-legume (Figure 3), data are shown for 'yield-stocking rate' combinations for which the pasture yield balanced the feed requirements of the stocked cattle without feed supplements. Thus, each data point has a different stocking rate: Natural with 7 t DM yield ha^{-1} is stocked by 2.4 AU ha^{-1}; Natural with 5 t DM yield ha^{-1} by 1.4 AU ha^{-1}; Natural with 2.5 t DM yield ha^{-1} by 0.6 AU ha^{-1} and Grass-legume by 2.1 AU ha^{-1}. For fertilized Brachiaria, results are shown for all generated yield-stocking rate combinations (Figure 4).

In Natural, the PEII declined with increasing yield because of the inverse relationship between herbicide use and weed-suppressing capacity of above-ground biomass (Figure 3a). On the contrary, the amount of N leached increased with yield because of increased losses from urine and manure by a larger number of stocked animals. All Naturals had a net loss of soil-C via CO_2 because SOC levels 25 years after forest clearing were lower than those of the original forest soil (Figure 3b). Total simulated C loss of the Natural with a yield of 5 t DM ha^{-1} was 25 t ha^{-1}, which compares well with a value of 21.8 t ha^{-1}

20 years after forest clearing as computed by Veldkamp (1993). Higher above-ground production was accompanied by higher below-ground production, and the loss of soil-C decreased with increasing yields. Contrary to this trend, rates of yearly N_2O emission increased with increasing yield (Figure 3b). With higher yields, more N is cycling through the system via manure and urine returns from a larger number of stocked animals. Calculated rates of 3-10 kg N_2O-N ha^{-1} y^{-1} were higher than the values of around 3 kg N ha^{-1} y^{-1} observed by Veldkamp et al. (1998). The yearly NO emission rates had the same pattern as those of N_2O (data not shown). The soil N balance was negative for all Naturals, with N mining rates increasing with increasing yield because of higher losses from urine and manure and because of higher removal via meat (Figure 3c).

The PEII of Grass-legume was zero because no herbicides were used (Figure 3a). The N leaching loss was in the same order of magnitude as that of Naturals with relatively high yields and high stocking rates. Grass-legume had a net sequestration of CO_2-C because of relatively high SOC levels (Figure 3b). The high SOC is a result of the relatively high root/shoot ratio of Brachiaria, i.e. 12.6, compared to that of Natural, i.e. 5.1, and a deeper rooting depth (Veldkamp, 1993). The yearly N_2O emission rate of Grass-legume was higher than that of Naturals because of the extra amount of N in the soil from microbial fixation (Figure 3b). The simulated rate of 13 kg N_2O-N ha^{-1} y^{-1} is a bit higher than the 5 kg ha^{-1} y^{-1} measured by Veldkamp et al. (1998). Because of N fixation by the legume, the soil N balance was zero and no N mining occurred (Figure 3c).

The major trends of the sustainability indicators in fertilized Brachiaria were the same as in the Naturals. PEII decreased with increasing yield and the amount of N leached increased (Figure 4a). The latter was not only an effect of increasing stocking rate with increasing yield, but more so of the increased use of fertilizer and the associated N losses. The amount of fertilizer applied depended on the combination of target yield level and stocking rate, and varied between 0-280 kg N ha^{-1}. With yield levels below 5-6 t DM ha^{-1}, there was a net loss of soil-C, and with yield levels above 5-6 t DM ha^{-1}, there was a net sequestration (Figure 4b). Rates of yearly N_2O emission increased with increasing yield. Highest emission levels were about 19 kg N_2O-N ha^{-1} on pastures producing 11 t DM yield (about 22 t total production) with 280 kg fertilizer N ha^{-1}. This value compares well with a measured value of 23 kg ha^{-1} on a Brachiaria producing 26 t above-ground DM fertilized with 300 kg fertilizer N ha^{-1} (Ibrahim, pers. comm.; Veldkamp et al., 1998). Because of the fertilizer application, the soil N balance was zero and no soil N mining occurred (data not shown).

Economic viability

The results of the LP scenarios are given in Table 5. With both 1996 and 1997 meat prices, fattening systems generated a higher economic surplus than breeding systems. With 1996 prices, the use of Natural with a production of 15 t DM ha^{-1} gave the highest economic surplus, both in breeding and in fattening systems. The negative soil N balances, however, indicate that these production levels are unsustainable. When Natural production decreased to 10 t DM ha^{-1}, economic surpluses decreased to 50-55% of the value at 15 t DM ha^{-1}. With a production of 5 t DM ha^{-1}, economic surpluses were negative and beef farming ceased to be profitable. The use of Grass-legume was economically an attractive alternative over Natural when the latter's production decreased from 15 to 10 t DM ha^{-1}: the economic surplus using Grass-legume was 76% of the value using Natural with 15 t DM ha^{-1} in breeding systems, and 96% in fattening systems. Compared to Natural, investment costs and labour use for weeding are relatively high in Grass-legumes. Due to high costs of establishment and fertilizers, the use of fertilized Brachiaria was not economically feasible in breeding systems (negative economic surplus), but realized an economic surplus of 89% of the value using Natural with 15 t DM ha^{-1} in the fattening system. In comparison to Natural, Grass-legume and fertilized Brachiaria were non-soil N mining, had a low PEII, sequestered CO_2-C and emitted more N_2O and NO. In addition, fertilized Brachiaria had a very high N leaching loss.

With 1997 prices, alternative pastures were economically more attractive. For breeding systems, the use of Grass-legume resulted in an economic surplus of 87% of the value using Natural with 15 t DM ha^{-1}, and the use of fertilized Brachiaria created an economic surplus of 17% of the value for Natural with 15 t DM ha^{-1}. For fattening systems, the alternative pastures were even equally to more attractive than the highest producing Natural: the use of Grass-legume had an economic surplus of 100% of the value using Natural with 15 t DM ha^{-1}, and the use of fertilized Brachiaria of had an economic surplus of 113%. The relative trade-offs among sustainability parameters between alternative pastures and Naturals were similar to those found at 1996 prices.

CONCLUSION AND DISCUSSION

Sustainability of tropical pastures is affected by pasture species, age and management, and its economic and environmental dimensions may move in opposite directions. Characteristically, many naturalized pastures in humid tropical lowlands are over-stocked with insufficient sources of N to sustain productivity levels (Uhl et al., 1988; Haynes & Williams, 1993; Hernandez et al., 1995). Over time, most sustainability indicators shift in a 'negative' direction: soil N stock declines due to mining, soil-C is lost (via CO_2 emission over time), more herbicides are needed to control invading weeds and profits decrease. On the other hand, some sustainability indicators move in a 'positive' direction: N leaching losses and N_2O and NO emission rates decrease over time. Alternative pastures based on grass-legume mixtures or fertilized improved species can realize relatively high, sustainable yields compared to naturalized pastures. Again, there are trade-offs among the sustainability indicators: with increasing yield level, N leaching loss and N_2O and NO emission rates increase ('negative'), but more CO_2–C gets sequestered, fewer herbicides are needed and profits increase ('positive').

The actual fate of the sustainability dimensions in cattle farming in humid tropical areas depends thus on two processes of change, *i*) degradation of current naturalized pastures and *ii*) introduction of grass-legume mixtures or fertilized improved species. What will eventually happen with pastures in a certain region depends to a large extend on the profitability of the various alternatives. Based on the profit levels (economic surplus) that were calculated in our case study, it may be expected that beef fattening farmers in the NAZ of Costa Rica will replace their degrading naturalized pastures by grass-legumes in the near future. Moreover, it was shown that the relative profitability of the alternative pastures increases with increasing beef prices. With the relatively high 1997 prices, the use of fertilized Brachiaria (300 kg N ha^{-1} y^{-1}) gave the highest profit of all alternatives. Whether alternative pastures really will be adopted does not only depend on profit, but also on availability and access to capital, level of technical knowledge, functioning of extension services (Joenje, 1995) and the use of land for speculation (Smith et al., 1997).

Sustainability parameters apply to different scales of time and space, and are perceived differently by different stakeholders (Fresco & Kroonenberg, 1992). For instance, the greenhouse effect has global implications and may not specifically be perceived as a 'problem' in the NAZ of Costa Rica. The use of pesticides, however, is typically a local problem when toxicity threatens biological values in the area. Even then, even though environmentalists often perceive pesticide use as a threat, farmers may not share the same opinion. Moreover, though different sustainability parameters may refer to the same environmental issue, their relative importance may vary substantially. For instance, CO_2 is much a more important contributor tot the greenhouse effect than N_2O and NO (IPCC, 1995). Finally, the relative importance of the various sustainability dimensions should be properly weighed in the area under study. For instance in the NAZ of Costa Rica, the use of pesticides in pastures is relatively low, i.e. 0.7-0.9 kg active ingredients of herbicides ha^{-1}, compared to the use of pesticides in bananas, i.e. about 45 kg active ingredients ha^{-1} (Castillo et al., 1997). Also, N pollution of water resources via leaching from the soil is (currently) not a threat because of the high amounts of rainfall and fast drainage of water to the Caribbean Sea. On the other hand, the CO_2 sustainability dimension of pastures may be relatively important: the replacement of degrading naturalized pastures by grass-legumes or fertilized improved grasses could change the CO_2 balance of pastures over a 20 year period from 30 t ha^{-1} net emission (Figure 3b) to up to 20 t ha^{-1} net sequestration (Figure 4b), implying a total sequestration 'gain' of 50 t ha^{-1}. For comparison, Navarro Monge (1996) estimated the amount of C stored in four different forest types in the NAZ of Costa Rica at 82-163 t ha^{-1}. In an effort to mitigate the greenhouse effect, Costa Rica intends to pay US$10 per t C fixed by forest in the context of a joint implementation program with industrialized countries. It could be reasoned that if fertilized pastures were recognized as means of C sequestration, cattle farmers could effectively be involved in the effort to mitigate the greenhouse gas effect. All in all, stakeholders and policy makers concerned with land use should realize the often conflicting nature of the various dimensions of sustainability.

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Table 1. Main characteristics of some example pasture alternatives modelled by PASTOR. All pastures are stocked by 2 AU ha^{-1}.

	Natural-10	Grass-legume	Brachiaria	Type[1]
Yield/removed biomass by herd (t ha^{-1} y^{-1})	5	5	5	O
Metabolizable energy content (Mcal kg^{-1})	2	2.3	2.5	I
Crude protein content (%)	8	11	12	I
Deficit in crude protein to feed herd (kg AU^{-1} d^{-1})	0.2	0	0	O
Depreciation time (y)	100	15	15	I
N fertilizer application (kg ha^{-1} y^{-1})	0	0	106	O
Herbicide use (kg active ingredients ha^{-1} y^{-1})	1.1	0	1.4	O
Costs (US\$ ha^{-1} y^{-1})	39	47	154	O
Total labor use (d ha^{-1} y^{-1})	1.9	3.2	3.4	O

[1]: I = PASTOR input, O = PASTOR output

Table 2. Mean properties of SFW soil as used in the soil N balance of PASTOR.

Property	Unit	Value
Atmospheric N deposition	kg ha^{-1} y^{-1}	10
N fixation by free-living micro-organisms	kg ha^{-1} y^{-1}	6
N leaching loss manure and urine	fraction	0.55
N leaching loss fertilizer	fraction	0.40
Total N recovery manure and urine	fraction	0.30
Total N recovery fertilizer	fraction	0.40

Table 3. Main characteristics of beef breeding and beef fattening systems modelled by PASTOR.

Variable	Value	Type[3]
Breeding herd[1]		
Maximum age females (y)	11	I
Liveweight gain males first year (kg hd^{-1} d^{-1})	0.65	I
Liveweight gain females first year (kg hd^{-1} d^{-1})	0.52	I
Calving interval (month)	14	I
Age at first calving (month)	31	I
Age of selling calves (month)	8	I
Costs (\$ $herd^{-1}$ y^{-1})	688	O
Labor use (d $herd^{-1}$ y^{-1})	60	O
Sold calves (kg $herd^{-1}$ y^{-1})	3714	O
Sold cows (kg $herd^{-1}$ y^{-1})	1504	O
Required metabolizable energy (Mcal $herd^{-1}$ $month^{-1}$)	22452	O
Required crude protein (kg $herd^{-1}$ $month^{-1}$)	1066	O
Fattening herd[2]		
Liveweight gain males (kg hd^{-1} d^{-1})	0.5	I
Liveweight gain females (kg hd^{-1} d^{-1})	0.4	I
Liveweight at selling males (kg)	450	I
Liveweight at selling females (kg)	400	I
Costs (\$ $herd^{-1}$ y^{-1})	488	O
Labor use (d $herd^{-1}$ y^{-1})	35	O
Sold calves (kg $herd^{-1}$ y^{-1})	13982	O
Required metabolizable energy (Mcal $herd^{-1}$ $month^{-1}$)	23136	O
Required crude protein (kg $herd^{-1}$ $month^{-1}$)	1134	O

[1]: Herd size: 41 AU; [2]: Herd size: 38 AU; [3]: I = PASTOR input, O = PASTOR output

Table 4. Meat prices in US$ in 1996 and 1997 per kg liveweight of animals in different quality classes.

Meat class	1996	1997
Male and female calves of breeding system	0.89	1.06
Cows of breeding system	0.69	0.82
Male calves of fattening system	0.84	1.00

Table 5b. Economic viability and sustainability parameters in beef breeding and beef fattening systems. Prices 1997.

Name	Ec. surplus (US$ ha^{-1} y^{-1})	SR [1] (AU ha^{-1})	NBAL [2] (kg N ha^{-1} y^{-1})	PEII [3] (ha^{-1} y^{-1})	NLEA [4] (kg N ha^{-1} y^{-1})	CO_2-C [5] (Mg C ha^{-1})	N_2O-N [6] (kg N ha^{-1} y^{-1})
Breeding							
Nat15	162	2.6	-63	9	59	18	10
Nat10	88	1.6	-32	14	36	25	6
Nat05	- [7]	-	-	-	-	-	-
Gleg	141	3.0	0	1	68	-10	12
Brfert	28	4.9	0	5	223	-30	23
Fattening							
Nat15	325	2.7	-63	9	62	14	12
Nat10	183	1.6	-32	14	36	25	6
Nat05	13	0.7	-3	27	16	31	3
Gleg	326	3	0	1	68	-10	12
Brfert	366	4.75	0	6	228	-27	21

[1]: Stocking rate; [2] : soil N balance; [3]: Pesticide Environmental Impact Index; [4]: amount of N leached; [5]: amount of CO_2-C emitted (positive values) or sequestered in soil organic carbon (negative values) at 25 years after forest clearing; [6]: rate of yearly N_2O-N emission, [7]: economic surplus is negative and no farming occurs.

FIGURE CAPTIONS

Figure 1 Location of the study area in the Northern Atlantic Zone of Costa Rica.

Figure 2. Observed (solid dots; bars are ± standard deviation) and DNDC-simulated (lines) Soil Organic Carbon, SOC, (a), N_2O-N emission (b) and NO-N emission (c) from pastures on Inceptisol in the NAZ versus years after deforestation. In (a), ◆ is SOC in 0-10 top soil, and ● is SOC in 10-20 cm top soil (mean values, no standard deviation available). SOC data as measured by Veldkamp (1994) and Veldkamp et al. (1992); N_2O and NO data derived from Keller et al., (1993).

Figure 3. Sustainability indicators versus yield for Natural (◇,◆) and Grass-legume pastures (□,■). Closed symbols refer to the left axis, open symbols to the right axis. Sustainability indicators are the Pesticide Environmental Index Indicator, PEII (◆,■) and the amount of N leached, NLEA (◇,□), (3a); the amount of C emitted (positive values) or sequestered (negative values), (◆,■) and the emission of N_2O-N (◇,□), (3b); the soil N balance, NBAL (◆,■), (3c).

Figure 4. Sustainability indicators versus yield for fertilized Brachiaria: Pesticide Environmental Index Indicator, PEII (◆) and the amount of N leached, NLEA (◇), (4a); the amount of C emitted (positive values) or sequestered (negative values), (◆) and the emission of N_2O-N, (◇), (4b).

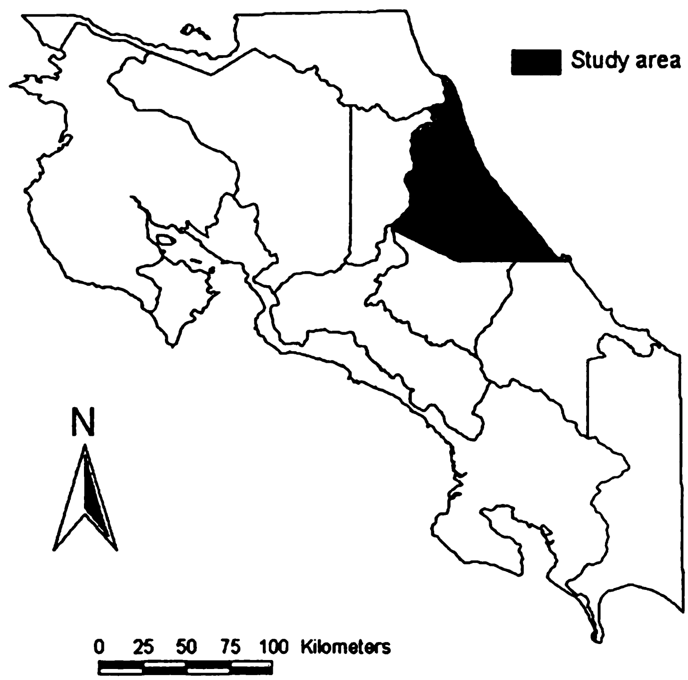
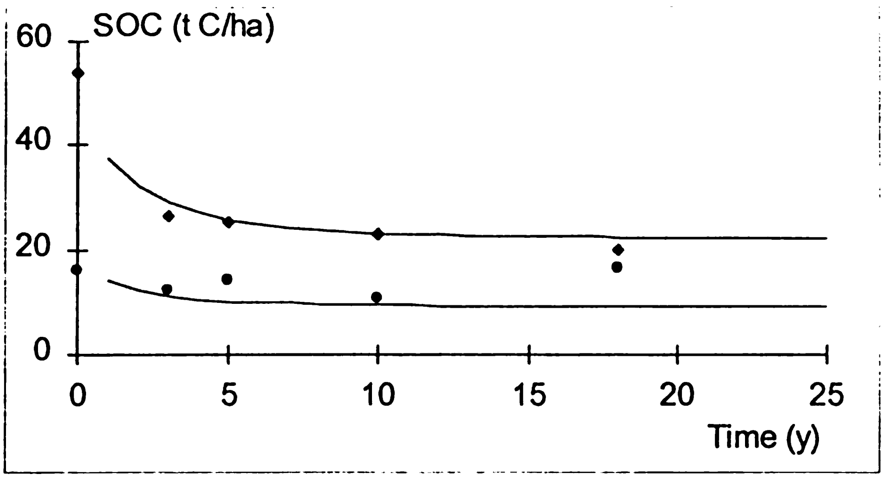


Figure 1.



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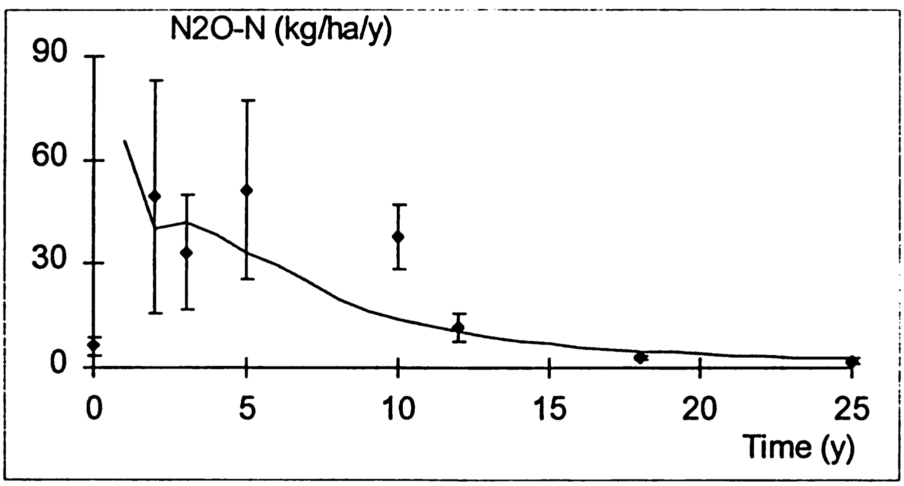

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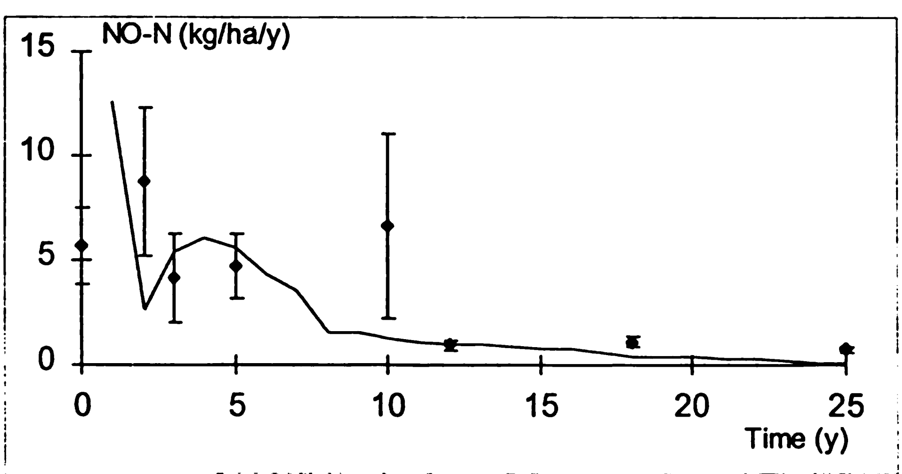

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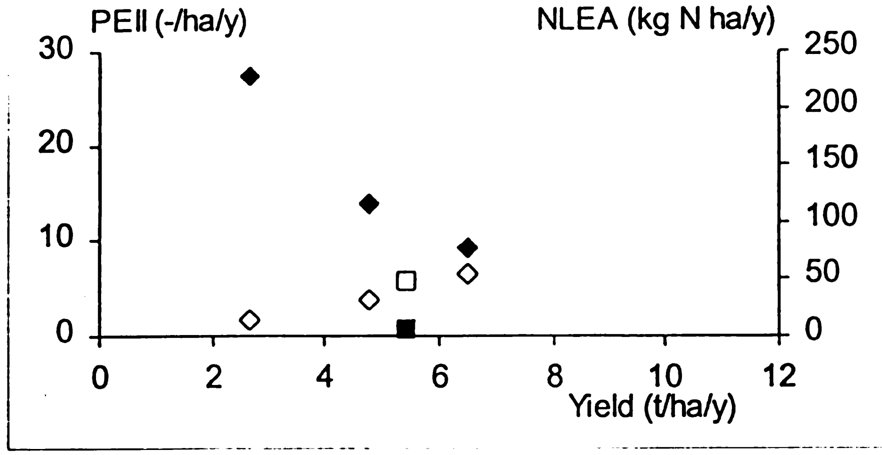
Figure 2



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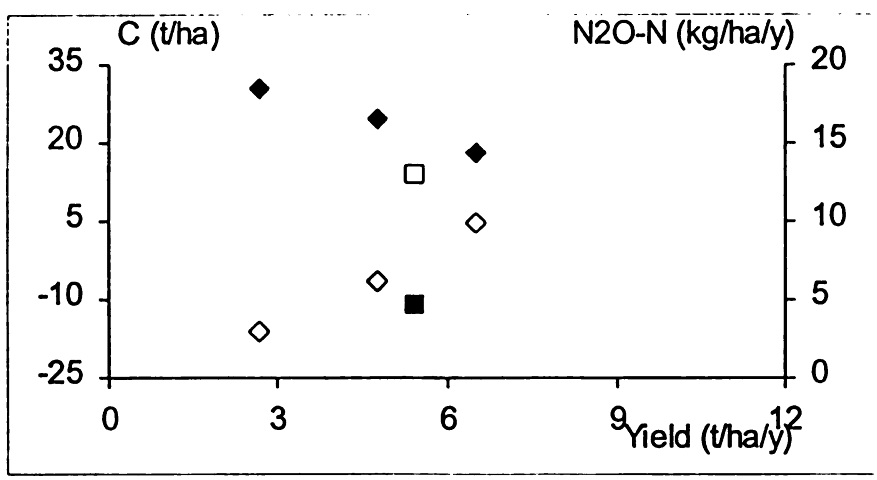

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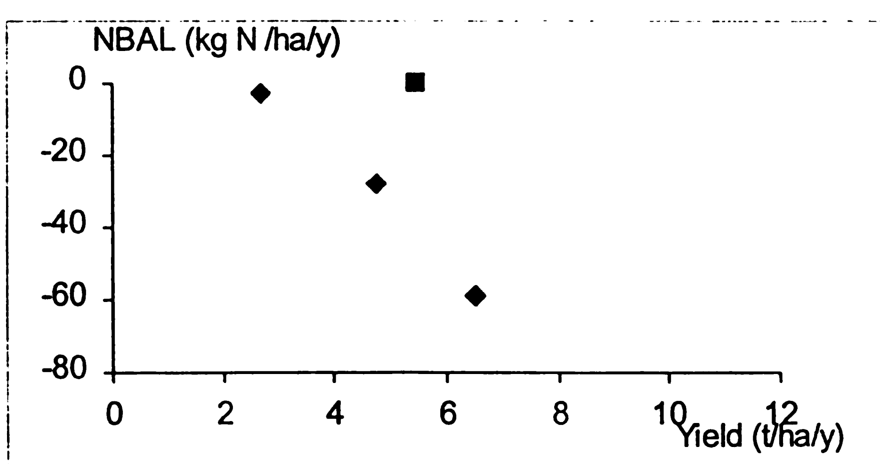

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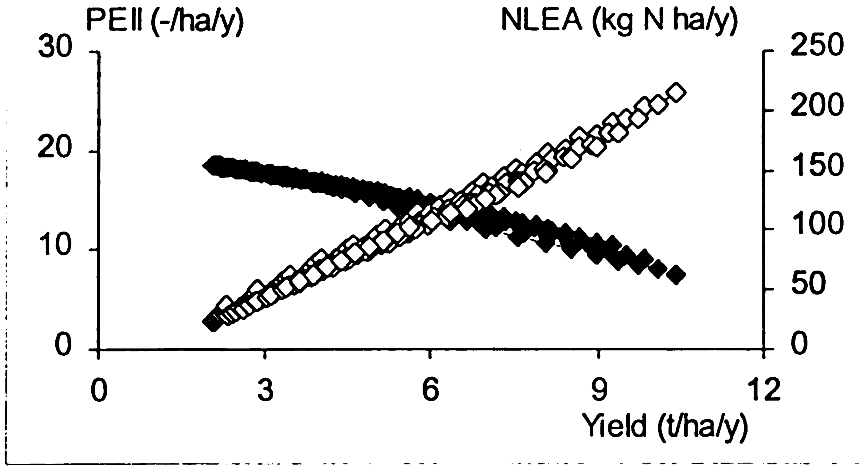
Figure 3



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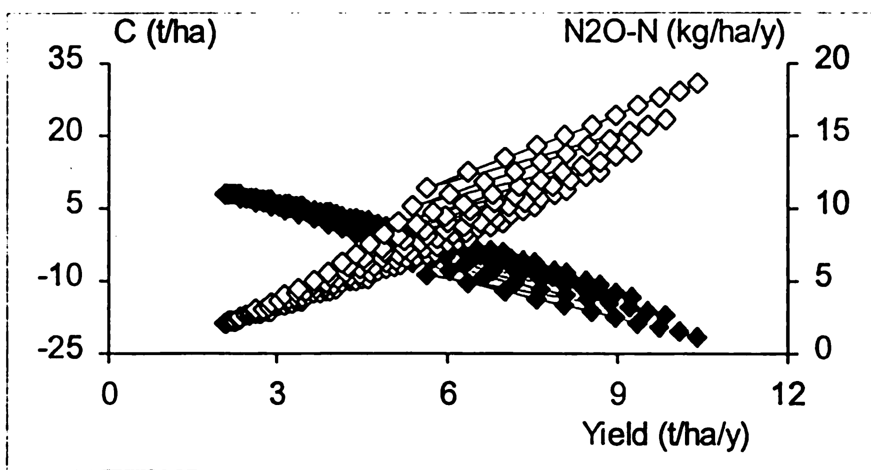

4b

Figure 4.