DYNAMICS OF THE AGRICULTURAL FRONTIER IN THE AMAZON AND SAVANNAS OF BRAZIL: SIMULATING THE IMPACT OF POLICY AND TECHNOLOGY

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Abstract

Simulation of future land use shows that the synergistic effect of favorable policies and technologies can control frontier expansion and achieve environmental protection, including carbon sequestration, without sacrificing production. Policy is a pre-condition for technology adoption, while policy without technology threatens future productive capacity. Key elements of favorable policies and technologies are identified.

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1 Introduction

The last 25 years have seen a rapid and uncontrolled expansion of the agricultural frontier in two vast, sparsely populated areas of Brazil: the Amazon tropical moist forest and the savanna, the latter being known as the Cerrado in Brazil. While internationally, deforestation in the Amazon is regarded as one of the most notorious environmental disasters, there is minimal international knowledge or concern about frontier expansion in the Cerrado. Within Brazil, awareness of the worldwide ecological services provided by the Amazon is growing rapidly. However, a number of prominent Brazilians believe their country should be compensated by the international community for the production it forfeits by preserving the Amazon. In contrast, Brazil values the cerrado primarily for its current and potential contribution to agricultural production, although recently awareness of the ecological implications of intensification is beginning to emerge. Thus in both ecosystems there is a growing perception of the tradeoff between production and the environment. Although scientific studies on these issues are emerging, they are primarily unidisciplinary in-depth studies in limited areas. The challenge now is to synthesize the available economic and ecological information in order to provide a rational basis for government and technology policy decisions. This paper contributes to this objective by simulating the impact of policy and technology on land use change in the Amazon and cerrado ecosystems of Brazil up to the year 2020. The results are not intended to be used for predictive purposes, but rather as a tool for developing a strategy for sustainable land use.

We begin by examining the driving forces behind past land use change in order to identify future scenarios depicting plausible changes in the driving forces. A land use model is then used to simulate the impact of these changes, and derive implications for policy and technology development.

2 Land use change

Following Mueller et. al.[1] we delimit the cerrado according to the EMBRAPA's [2] vegetation map, including within it the transitional area between the cerrado and the tropical moist forest in northern Mato Grosso, a total of 165 million ha. (Figure 1)[1]. The dominant vegetation (67%) consists of grasslands with small twisted trees and gallery forests in riparian areas. Rainfall varies from 1000mm to 1800mm with a dry season of three to six months. Soils are predominantly oxisols (50%), with high levels of acidity and phosphorus deficiency [3]. For the Amazon we take the Northern Region of Brazil (Figure 1)[2], an area of 350 million ha. Soils are predominantly acid (oxisols and ultisols), the vegetation consists primarily of tropical moist forest, and annual rainfall is generally over 2000 mm. with a dry period of three to four months [4].

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[1] This corresponds to most of the states of Mato Grosso do Sul, Goiás, Minas Gerais, and parts of Bahia, Piaui, Maranhao and Mato Grosso.

[2] States of Pará, Amazonas Rondônia, Amapá, Roraima, Acre, Tocantins.

Contrary to popular perception only 6% of Legal Amazonia[3] had been cleared by 1988 [5]. Within the Amazon there are two broad patterns of land use following deforestation:large scale extensive ranches (as in Para/Tocantins) which are often abandoned when land ownership is established [6]; and slash and burn agriculture, (as in Acre-Rondonia), in which annual crops are planted initially after deforestation, followed by pasture, which is sold out to ranchers, while the proceeds are used to acquire and deforest new land [7,8]. Deforested areas in the Amazon absorbed considerable numbers of resource poor migrants (population in Acre/Rondonia grew by over 11% p.a. in 1970-1980), and contributed almost 12% of Brazil's rice and cassava production in 1990 [1]. Agricultural productivity in this ecosystem may depend however on continuing deforestation as yields tend to decrease after a few years. During a period of declining deforestation (1984-1990) the yield of rice, usually the first crop sown after deforestation, declined by 23% [1]. Amazonian beef production has barely been able to satisfy local demand [9].

Human intervention has been far greater in the Cerrado than in the Amazon. Thirty-five percent of the savanna has been cleared, and another 56% is used for extensive grazing and timber exploitation [3]. Cattle ranching is the dominant enterprise everywhere, with the proportion of planted pasture (75% of cleared area in 1985) being much higher in the older settlement areas close to major markets(Mato Grosso do Sul, Minas Gerais), than in frontier areas, where it occupies less than half the cleared area. Contrary to expectation the proportion under capital intensive crop production is uniformly around 20% of the cleared area, even in frontier areas more

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3 Legal Amazonia includes the Northern Region plus the states of Mato Grosso and Maranhao.

than 2000 km. from ports [1]. Small scale dairying is the dominant enterprise in riparian areas, with small scale producers supplying 30% of milk production in Minas Gerais state [10]. The Cerrado makes a very substantial contribution to agricultural production (35% and 17% of national soybean and maize production in 1990), and contains over a third of Brazil's cattle. The Cerrado also supplied 40% of Brazil's wood production during 1980-1990 [11]. Land ownership is highly concentrated with farms > 1000 ha. occupying 59% of the area. As a result population increased by less than 3% p.a. during 1970-1980, in spite of rapid frontier expansion [1].

Land use change in the Amazon and the Cerrado has had major implications for greenhouse gas emissions from biotic sources. Schroeder and Winjum [12] estimate that Legal Amazonia emits 174-233 million t of carbon per year. The location of hydroelectric dams within Legal Amazonia is estimated to have contributed 0.26 million t of methane and 38 million t of carbon dioxide in 1990. Fearnside [13] estimates that the impoundment behind the Balbina dam increased emissions by 20 times more than the generation of an equivalent amount of power from fossil fuels. These contribute to climatic warming.On the positive side, government subsidies increased sugar cane production for automotive alcohol in the cerrado from 0.3 million t in 1970 to 1.3 million t in 1980, thus reducing carbon emissions from fossil fuels [3].

Other ecological impacts include habitat fragmentation and degradation which has occurred at an annual rate of 3.8 million ha. in Legal Amazonia during 1978-1991 [13]. In the cerrado some types of vegetation such as mesotrophic woodland, and fauna such as the pampas deer, are now becoming rare [3]. Drastic land use changes would also be expected to cause disruption of ecosystem functions such as watershed protection, nutrient cycling and soil conservation. Selective logging in the Amazon is also estimated to have a devastating impact, leading to 40% mortality in the surrounding forest [14]. Mining activities, in addition to stimulating deforestation, have created health hazards: gold mining in the Tapajos river released 2000 t of mercury into rivers in 1980-1990 [15].

In the Cerrado soil losses in monocropped areas over a 6 year period ranged from 50 t/ha. to 173 t/ha. compared to 0.8 t/ha. under natural vegetation [3]. Agriculture is estimated to be responsible for 50% of the organic matter that enters waterways [11]. Soil losses, sedimentation could have serious off-site effects because the Cerrado is part of the watershed of major rivers such as the Parana, and drains into the Pantanal, one of the largest wetlands in the world. Results from long term trials show that continuous tillage of monocropped rice in the savanna reduces soil aggregation and porosity, resulting in lower water retention and aeration, and a reduction in macrofauna biomass and microbial N and P. These effects are reflected in rice yields which declined by 54% over 6 years [17]. Pesticide use in the Cerrado is estimated to be 1.8 kg. active ingredient (a.i.)/ha. of crops, equivalent to 9% of national consumption, compared to a national average 0.75 kg. a.i./ha. [18]. Pasture degradation, leading to soil loss and run-off is believed to be widespread in both the cerrado and the Amazon, but no quantitative estimates of the extent of degradation are available. Widespread deforestation of gallery forests, and sedimentation is reported in riparian areas of small scale dairy production in the cerrado [19].

3 Driving forces behind land use change

In the Amazon the rate of deforestation based on remote sensing data is estimated to be between 1.5 to 2 million ha. per year between 1978 and 1988 [5]. The fundamental cause of this rapid rate of frontier expansion has been identified as the Brazilian style of development [20,1], characterized by high levels of land concentration (Gini coefficient of 0.85 in 1985:[21], and subsidies for mechanized agriculture, as a result of which 70% of rural households are estimated to be landless [22]. Thus the poor, assisted by government settlement programs, migrated to the Amazon, where successful settlers are able to earn incomes four times higher than the minimum wage [21]. The frontier was also an escape valve for the speculative capital of the rich. High unstable inflation (over 80% in the 1980s:[23], land titling linked to deforestation, and expansion of rural credit at an annual rate of 24% during the 1970s [24], at negative real interest rates (-25% to -35% in 1979-1986:[21]) increased the speculative demand for land, and pushed land prices well beyond their productive value [25]. These artificially high land prices impeded acquisition of cleared land by the poor, and exacerbated the existing inequality in land distribution. It also stimulated squatting by the poor on abandoned cattle ranches leading to violent social conflict. Simultaneously it provided a good market for land deforested and sown to pasture by small holders at the frontier, thus encouraging small holders to sell out, and deforest new land. Access to frontier land was provided by the Brazilian government's construction of penetration roads into the Amazon for geopolitical reasons. Satellite data show that most of the changes in land cover between 1970 and 1980 occurred along penetration roads [5].

Quantitative estimates of the forces described above relate mainly to the speculative demand for land. Brandao and Rezende [26] show that 6% of the increase in land prices in 1966-1989 was due to subsidized credit, and 28% to macroeconomic instability. Thus macroeconomic conditions appear to be more important than direct government subsidies as the driving force behind speculative land acquisition. Ledec [27] shows that less than 10% of Panamanian deforestation was due to credit, but that each km. of penetration roads (which in some cases doubled land prices) led to up to 2000 ha. of deforestation. Southgate [28] quantifies the impact of tenure security on deforestation in Ecuador. These estimates confirm the importance of speculative land acquisition, but leave unquantified its importance relative to the search for a better life by the poor.

Conversion of the natural ecosystem in the Cerrado has been as rapid as in the Amazon (2 million ha. per year in 1970-1985), including an annual deforestation rate of 0.35 to 0.45 million ha.[1,11]. The main driving force has been the search for cheap land, which in turn was driven by government policies (described above), which inflated land prices beyond their productive value [1]. The development of highly productive, capital and agrochemical intensive soybean technologies adapted to the Cerrado by the national research institute (EMBRAPA), and booming world markets for cerrado commodities during the late 1970s also increased the demand for land. In certain frontier areas, such as the center-north of Mato Grosso, incentives for private settlement programs, such as subsidized credit, uniform minimum output prices and fuel prices, support for processing industries, and access to public land, enabled farmers at the frontier to duplicate the capital intensive cropping systems of the older settlement areas [29,30,1]. Road construction, aimed at incorporating Brasilia and the Amazon into the mainstream economy, passed through the Cerrado, thus facilitating the search for cheap land. As in the case of the Amazon, these driving forces, with the exception of the speculative demand for land, are largely unquantified.

4 Emerging new trends

Major changes in government policy have recently taken place in Brazil. A macro stabilization initiative known as the Real Plan has de-indexed prices from ex-post inflation, and set a ceiling for the currency at Real1 = $1. This has reduced inflation from 2000% in 1993 to 26% by the end of 1995 and increased the returns to financial assets, the real interest rate being 28% in 1995[31].Subsidies have been removed, land titling is no longer linked to deforestation, the trade regime has been liberalized, and construction of penetration roads has been slowed down. Deforestation is taxed, although the tax rate is too low to make sustainable forestry viable [11].

Frontier expansion appears to have slowed down. Using remote sensing data Skole et.al.[5] and Moran [32] show that current rates of deforestation are about half of what they were in the late 1980s. Population growth rates in the Amazon in 1980-1991 were almost half of what they were in 1970-1980. The increase in pasture area in Para/Tocantins declined from 1.95 million ha. in 1975-1980 to 1.3 million ha. in 1980-1985 [1]. The decline in deforestation appears to be primarily a result of reduced incentives for land speculation, resulting from the policy changes described above. Declines in the speculative demand for land impede small holders' access to new land, as do reductions in penetration road construction, and government settlement programs.

Data on frontier expansion in the Cerrado are not available, but field interviews by one of the authors in Mato Grosso indicate that frontier expansion is decreasing, because of steep declines in the profitability of soybean due to high interest rates, removal of subsidies and uniform minimum output prices, and yield declines due to the build up of soil physical problems and pests and diseases. In addition macroeconomic stabilization has reduced the speculative demand for land. These factors have led to a decline of over 20% in land prices in 1995 [31] and reduced incentives for frontier expansion.

While changes in government policy are discouraging frontier expansion, a new private sector driven threat to deforestation appears to be emerging. In order to maintain the viability of soybean in areas far from ports, such as Mato Grosso and Balsas, the powerful coalition of large scale soybean producers and agroindustry is lobbying for the construction of export corridors to the northern Atlantic and Pacific coasts. This is likely to expand the agricultural frontier in the Cerrado into the Amazon, causing massive deforestation. Augmenting this effect is the expected continuing increase in wood prices [33] which makes logging a lucrative way of recuperating the cost of clearing land for agricultural production. Reflecting this is an increase of 170% in the Amazon's wood production between 1980 and 1990, as a result of which the Amazon's contribution to national wood production from native forest increased from 9% to 23% during this period, while wood from plantations remained constant at around 2% of national production [11].

Counteracting these negative forces are major advances in research and technology development. Tropical moist forests, which ecologists had previously regarded as highly fragile and difficult to rehabilitate, are now seen as resilient. This provides opportunities for managing secondary growth so that some of the original ecological functions of the primary forest can be fulfilled [34]. Satellite data from an older settlement area, Altamira in the Eastern Amazon, show that secondary growth on land abandoned after logging or livestock/crop production is the predominant land cover after primary forest, occupying 24% of the total area. Sixteen percent of this is advanced secondary succession, i.e. similar to mature forest. Between 1985 and 1991 secondary growth increased by 73% [35]. Thus there are considerable opportunities for better management of secondary growth, which currently has minimum economic value. Another interesting finding is that improved grass pastures which occupy 31 million ha in the cerrado [1] appear to be acting as a net sink for carbon [36]. Other promising technological advances with beneficial ecological effects include a crop-pasture rotation system which improves soil physical and chemical properties [37], and a highly productive legume, *Arachis pintoi*, which persists under heavy grazing pressure, and provides 40 to 80 kg nitrogen/ha/year [38].

An interesting new development is the emergence of Global Environmental Markets (GEM), through which environmental services such as carbon storage could be traded internationally. This is a potential mechanism through which developing countries could capture the benefits of providing global environmental services, and could be a powerful incentive for the adoption of sustainable land use systems. If these services can be provided more cheaply by developing countries, GEMs could also be a mechanism for reducing the costs of meeting global environmental targets [39,40,21]. Internationally the possibility of Joint Implementation of carbon emission cutbacks has been formally recognized by The Framework for Climate Convention, although a number of objections to emission targets have been raised [41]. Examples of Joint Implementation are beginning to emerge, such as the funding of carbon sequestration projects in Mexico and Poland by Norway's fuel tax. US utility companies, in anticipation of regulation and from image considerations, are making carbon sequestration investments in developing countries [42]. Pharmaceutical companies are making biodiversity prospecting deals in which developing countries provide plant samples in return for royalties from successful drugs developed from these samples [43]. Studies show that the potential for GEMs is high, particularly for carbon storage. The estimated value of carbon storage by forests in the Amazon ($976 to $7200/ha) is, for example 2 to 30 times the value of alternative land uses [21]. Improved pastures in the Colombian savanna have also been shown to be sequestering around 3tC/ha. per year [36]. It should be pointed out that GEMs could be abused unless there is some degree of societal control. International trade in toxic wastes could occur, or unfair deals could be struck due to asymmetry in information and bargaining power.

The overall conclusion is that many of the government policies which stimulated frontier expansion are beginning to be dismantled. In addition, new ecological paradigms, technological advances, and international mechanisms for compensating the providers of global environmental services are emerging. On the negative side, a new private sector driven force for deforestation may be appearing. If the government continues its economic reforms and controls the new threats to deforestation, there could be a unique opportunity for achieving major advances in sustainable management of frontier areas in Brazil [45].

5 Simulating land use change

5.1 The model

Land use models may incorporate quantitative calculations for at least some of the driving forces [45, 46, 42], or the driving forces may be exogenous to the models, as parts of externally defined scenarios [47, 48] . While the latter approach sacrifices quantitative precision, it permits the incorporation of a larger range of relevant variables, thus enhancing its usefulness for policy purposes. The previous sections illustrated the complexity of forces behind land use change in the Amazon and cerrado, and the paucity of quantitative estimates of the impact of driving forces. Given this situation we follow the scenario approach by adapting a simple land use model for Latin American ecosystems [47,49,50] to the specific characteristics of the cerrado and tropical moist forest (Amazon) ecosystems of Brazil.

Land in each ecosystem may be distributed into seven land use categories (LUC) represented by squares in Figure 2, with different structural, functional and productive characteristics for each of the two ecosystems. Each year land shifts from one LUC to others, at a rate determined by the types of human activities and natural processes, and their intensity. Activities are represented by circles in Figure 2, and the intensity of activities is determined by exogenously defined scenarios described below. Each scenario yearly specifies the proportion of each LUC affected by relevant activities, and the rate of conversion to other LUCs. The arrows in Figure 2 represent the permitted activities on each LUC, and the permitted flows of land among LUCs.

The structure of the model consists of a set of difference equations for each ecosystem:

$$S_{t+1}^{kv} = S_t^{kv} + \sum_i I_{t,t+1}^{ikv} - \sum_j O_{t,t+1}^{kjv} \tag{1}$$

where S^{kv} = Surface of land (sq. km) in a specified land use category (LUC) for a specified scenario.

I^{ikv} = Inflows of land to LUC k (sq. km/year) from other LUCs moving into k as a result of carrying out specified activities within a given scenario.

O^{kjv} = Outflows of land from LUC k to other LUCs j as a result of carrying out specified activities in k within a given scenario.

v = scenario under consideration (v = 1A, 2A, 1B, 2B)

k = LUC under consideration ($k = 1 \ldots\ldots 7$, denoting the rectangles in Figure 2).

i = LUC contributing land to LUC k ($i = 1 \ldots\ldots 7$)

j = LUC receiving land from LUC k ($j = 1 \ldots\ldots 7$)

t = time

$$I_{t,t+1}^{ikv} = f^{ikv} \ (A_{t,t+1}^{ikv}) \tag{2}$$

$$O^{kjv} = f^{kjv} \ (A_{t,t+1}^{kjv}) \tag{3}$$

A^{ikv} = process or activity operating in LUC i under scenario v, denoting the circles in Figure 2.

A^{kjv} = process or activity operating in LUC k under scenario v.

f^{ikv}, f^{kjv} = functions defined by the scenario v

For each activity operating within a LUC i or k, the functions f may be absolute rates (sq. km/year) either fixed or a linear function of time, or a fraction of the donor LUC, either fixed or changing linearly with time.

$$\sum_j O_{t,t=1}^{kj} \leq S_t^k \tag{4}$$

where S^k_{min} and S^k_{max} are parameters defined for each LUC k

$$S_{\min}^{k} \leq S^{k} \leq S_{\max}^{k} \tag{5}$$

GY_t = grain yield (t/ha), a linear function of time defined by the scenario for the relevant LUC.

SR_t = stocking rate (animals/ha), a linear function of time defined by the scenario for the relevant LUC.

WY_t = wood yield (cubic meters/ha), a linear function of time defined by the scenario for the relevant LUC.

Slash and Burn agriculture, in the Amazon, is represented as activity RC (deforestation)on a proportion of the Natural Ecosystem (NE), which then flows into the Agricultural Ecosystem (AG), from where after three years of shifting agriculture (SA) it passes to the Altered Ecosystem (ALT)[4], and then is reconverted to pasture and moves to the Grazing Ecosystem (GR). Large scale mechanized agriculture, in the Cerrado (PA) results from reconversion of NE to AG. A proportion of this land (depending on the scenario under consideration) moves to ALT every year as a result of degradation, while Activity PA continues on the remaining land. Ranching directly after deforestation is represented by flows from NE to GR following RC, from where a specified proportion (which varies by scenario) is abandoned each year, and moves to ALT, where it develops into secondary forest. Logging is represented as activity FE on NE, as a result of which it flows to ALT, from were it may be reconverted to AG

[4] ALT is a mosaic of secondary forest, agrosilvopastoral systems, fallow and abandoned land in which some features of the original ecosystem are still recognizable.

or GR. The nature of these flows result in ALT occupying a large proportion of the total area and this indicates the potential of ALT as a key entry point for interventions.

Data on the surface area of each LUC in 1970, 1980, and 1985 are compiled from various sources and given in Table 1. These data confirm that although NE is 13 times larger in the Amazon than in the Cerrado (in 1985), the area under human intervention is almost 7 times larger in the Cerrado. The dominant non-natural LUCs in both ecosystems are pastures which occupy over half the intervened area in both ecosystems, and ALT which occupies about 24% in the Cerrado, and 38% in the Amazon. Data on grain yields, and cattle stocking rates, given in Table 2, reflect the higher fertility of soils in the Amazon relative to the Cerrado, particularly in the few years after deforestation. Wood production in the Cerrado is mainly for fuel wood and charcoal, while saw logs and industrial roundwood production dominates in the Amazon. Cattle numbers are 4 times higher in the Cerrado than in the Amazon. Also, cattle production has intensified over time in the Cerrado, with stocking rates having doubled between 1970 and 1985, while in the Amazon stocking rates stagnated.

The data in Tables 1 and 2 form the starting point of the simulation exercise. The intensity of activities during 1970 - 1985 is based on past driving forces described above, and calibrated to the data in Tables 1 and 2. Simulation up to the year 2020 is then carried out by adjusting the intensity of activities and production according to the characteristics of specified scenarios.

5.2 Scenarios

We specify four scenarios, consisting of combinations of favorable and unfavorable government policies and technology development strategies. The characteristics of each scenario and its qualitative impact on the determinants of frontier expansion, production and the environment are summarized in Table 3. The specified intensities of selected activities on LUCs, flows between LUCs, ie the functions of equations (2) and (3) and specified yields and cattle stocking rates, for each scenario are given in Tables 4 and 5.

5.2.1 Scenario 1A

This combines unfavorable policy with a technology development strategy oriented towards increasing the productivity of individual commodities through high levels of agrochemicals, with environmental impact being very much a secondary consideration.

The success of the Real Plan is assumed to be jeopardized by the failure to achieve fiscal reform (the net internal debt of the public sector rose by 50% in 1995: [51]), and a ballooning current account deficit (estimated to be $22.4 bn in 1996:[51]). Government eases monetary policy under pressure from the private sector. Inflation starts to go out of control. Government increases interest rates, which worsens the fiscal position because of high public debt, and increases the real exchange rate. The result is a vicious circle of macroeconomic instability. Thus speculative demand for land remains high, as Brandao and Rezende's [26] analysis would lead us to expect, and frontier expansion continues. The profitability of industrial production and of capital intensive export crops, such as soybean in the Cerrado is threatened by high interest and exchange rates and the failure to lower the "custo Brazil" (high cost of taxation and infrastructure), and the government gives in to pressures to construct export corridors through the Amazon. Ad hoc regulatory mechanisms are used to prevent deforestation, but prove to be difficult to enforce. Attempts are made to improve income distribution by imposing contractual obligations on employers of agricultural and industrial labor. But this increases labor cost, and reduces employment. Thus the incentive for the poor to migrate to the frontier remains (Table 3).

These developments are captured in the model by specifying a high rate of conversion of the Natural Ecosystem for this scenario: by the year 2020, 0.45% of the Natural Ecosystem is reconverted annually to other uses in the Amazon, and 2.2% in the Cerrado (Tables 4 and 5). Consequently, simulation results (Tables 6 and 7) show that the Natural Ecosystem declines by 18% in the Amazon, and 72% in the Cerrado between 1980 and 2020.

Grain yields stagnate in the Cerrado. Soil and pest problems build up, but the only technology options for combating this are higher levels of agrochemical use, which aggravate these problems in the long run, and lead to lower profits under a regime of high interest rates. The export corridor however reduces marketing costs and opens up new land at the frontier (Table 3), and simulated crop area increases by 43% between 1980 and 2020 (Table 7). In the Amazon simulated crop area increases by 50% (Table 6), because of the high rate of deforestation resulting from the export corridor and the speculative acquisition of land (Table 3), and grain yields are maintained because of the high fertility of recently deforested land (Table 4). Deforestation also increases timber production in the Amazon more than five fold during the simulated period (Table 6). Because of the importance of speculative land acquisition in this scenario, the rate of pasture establishment and abandonment is high in both ecosystems. The growth in pastures is captured in the model by 55% of cleared land being devoted to cattle ranching in the Amazon (Table 4), and 88% in the Cerrado (Table 5). Pasture abandonment is captured by 8.5% of grazing land passing to ALT each year in the Amazon, and 6% in the Cerrado (Tables 4 and 5).The increasing trend in planted pastures however continues in established cattle ranching areas in the Cerrado, leading to increases in the stocking rate (Table 5), and a 77% increase in cattle numbers over the simulated period (Table 7).

Turning next to environmental impact, we estimate net carbon fluxes resulting from land use change by adapting the methodology used by Schroeder and Winjum [12]. For pastures in the Cerrado we incorporate the impact of burning native savanna pastures every four years.For carbon sequestration by improved pastures in the Cerrado we use a figure of 1tC/ha/year for grass alone pastures and 2 tC/ha/year for mixed grass-legume pastures, equivalent to 33% and 23% respectively of Fisher et.al's [36] estimate of carbon sequestration by well managed improved pastures in the Colombian savanna. This downward adjustment is made to take account of differences between farmers' and researchers'management, reductions in carbon accumulation over time [52] and the longer dry season and lower phoshorus availability in the Cerrado. Net carbon fluxes from tree crop systems, such as plantations and agroforestry systems are estimated using Dixon et. al.'s [53] methodology. Simulation results show that net carbon emissions in 1980 for the Amazon and Cerrado combined are around 172 million t, which is roughly consistent with Schroeder and Winjum's [12] estimate of 174 to 233 million t for the entire country in 1990. Simulated land use changes in the Amazon cause net carbon emissions to more than double to over 270 million t by the year 2020, mainly due to continuing deforestation and to decomposition and reburning of forest biomass residues as part of the process of pasture management. In the Cerrado however carbon sequestration by improved pastures compensates to some extent for carbon emissions due to deforestation, as a result of which net emissions in 2020 (70 million t) are virtually the same as in 1980 (Tables 6 and 7). Quantitative data on other environmental impacts are not available. The pattern of land use in this scenario imply however that environmental problems such as habitat fragmentation, soil degradation, off-site pollution and contamination and the disruption of ecosystem functions are exacerbated.

5.2.2 Scenario 2A

This scenario combines favorable economic, environmental and social policies with the same productivity oriented technology development strategy described in scenario 1A.

The economic situation improves: fiscal balance is achieved, inflation is controlled, permitting more moderate interest rates, political and economic stability is achieved, and the speculative demand for land declines. Reduction of interest rates and "custo Brazil", and a stable real exchange rate eases the pressure on manufacturing industry and export crops. Inflation control and economic growth increases employment and the purchasing power of the poor, reducing pressures to migrate to the Amazon (Table 3). Environmental and social policy changes are also achieved. Construction of penetration roads and export corridors are controlled, and taxes on environmental degradation are imposed. Farm to market roads are built in already deforested areas, stimulating local processing and distribution of cerrado and Amazon products. Social programs such as primary and secondary education, and improvement of social amenities in rural areas increase the opportunity cost of migrating to the frontier. Contractual obligations on employers of labor are dismantled, and employment opportunities increase (Table 3). At established frontiers there is better enforcement of property rights, reducing social conflict.

The above factors are captured in the model by marked decreases in the specified rates at which the Natural Ecosystem is converted to other uses. This falls to an annual rate of 0.1% of the Natural Ecosystem by 2020 in the Amazon, and 0.04% in the Cerrado. As a result of the decline in the speculative motive, a much larger proportion of cleared land is devoted to agriculture, at the expense of cattle ranches in both ecosystems (Tables 4 and 5). Reflecting these changes, simulation results show that the loss in NE by 2020 is 30% less than in scenario 1A in the Amazon, and 64% less in the Cerrado. In comparison with scenario 1A, the area in agriculture expands by over 5 million ha. in the Amazon, and by over 2 million ha. in the Cerrado (Tables 6 and 7).

Grain yields decline in frontier areas in the Cerrado, because soil and pest problems persist, and the lack of an export corridor reduces profitability. In crop areas closer to ports, compensatory increases in agrochemical use to combat soil and pest problems are now more feasible given the improved economic conditions. However, pollution taxes lower profitability because technologies for reducing agrochemical use do not exist. The net result is stagnant grain yields (Table 5).

Yields also stagnate in the Amazon because the reduction in penetration roads and the fall in the demand for pasture land by large scale speculators impedes access to new land. Small holders therefore recultivate old land, and yields decline, particularly as fallow management technologies do not exist in this scenario (Table 4). The profitability of cropping however increases because economic conditions improve, and farm to market roads increase farm gate output prices. Declining yields are therefore more than compensated by the increase in agricultural area, and grain production is well above the level in scenario 1A (Table 6). In both ecosystems while expansion in pasture area declines, cattle production on existing pastures is intensified and moderate increase in stocking rates begin to occur, because speculative motives have declined. Thus, cattle numbers are slightly higher than in scenario 1A in the Amazon, and 38% higher than scenario 1A in the Cerrado. Therefore, contrary to common belief, the decline in frontier expansion does not lead to declines in grain and cattle production. The decline in deforestation however results in major reductions in timber production in the Amazon, which in 2020 is only 46% of the quantity under scenario 1A (Table 6). As a result of the decline in deforestation net carbon emissions in the Amazon in 2020 are 72% of the level expected under scenario 1A, while in the Cerrado carbon emissions are reduced by 33% (Tables 6 and 7). Habitat fragmentation and disruption of ecosystem functions declines in both ecosystems, but contamination, pollution and soil degradation persist.

Thus this scenario implies that favorable policies are able to achieve significant reductions in frontier expansion, habitat fragmentation, and carbon emissions. However without resource management technologies, yields and profits decline, and on-and off-site resource degradation builds up.

5.2.3 Scenario 1B

In this scenario a new technology development strategy is introduced in an unfavorable policy environment similar to scenario 1A. The new technology development strategy takes a holistic approach oriented towards sustainable management of ecosystems. In addition to productivity, environmental protection is an important objective. Diversity in land use systems, dynamics of secondary vegetation and forest regeneration [54], sustainable management of natural forests as an alternative to selective logging [55], integrated nutrient and pest management, and amelioration of off-site resource degradation are key stones of the strategy. Economic valuation of non-market environmental goods and services is carried out to enable governments and technology developers to quantify tradeoffs between production and the environment.

The overall technology development strategy under this scenario in the Amazon is to protect the environment, while enabling local people to capture the benefits of providing global ecological services. The Cerrado is visualized as providing an outlet for private investment and economic growth, without damaging the environment, thus relieving pressure on the Amazon. Given the dominant role played by large scale farmers and agribusiness in the Cerrado, it is assumed that productivity oriented technologies for the Cerrado will be developed by the private sector. The major focus of the public sector in the Cerrado therefore is on public goods and the off-site effects of intensification.

Under this strategy, in the Amazon, technologies for intensifying and stabilizing production on small-holder food crop and pasture plots and for improving fallow management are developed. These technologies are not however economically viable because transport costs are high due to the lack of farm to market roads. Also incentives for recultivation of old land are low, because of penetration road construction and speculative demand for pasture land. Thus technology fails to slow down deforestation by the poor (Table 3). For the same reasons, ecologically sound technologies which could anchor small holders to their plots and provide some of the ecological services of primary forests, such as enriched secondary growth and agrosilvopastoral systems, and technologies for increased productivity of non-timber forest products, are not adopted. Technologies, such as reduced impact logging, which ameliorate habitat destruction and carbon emissions are developed, but prove to be less profitable than more environmentally destructive methods. (Table 3). Pasture abandonment on large scale ranches continues because of speculative land acquisition, in spite of the development of pasture renovation technologies.

In the Cerrado, in an environment of high interest rates, technologies which overcome on-site soil and pest problems are adopted if in addition they reduce operating cost.

Field work by one of the authors in Minas Gerais shows, for instance, that no-till systems, primarily diffused by the private sector, have recently been adopted by 53% of sample crop farmers in order to reduce land preparation costs and soil degradation. Many sustainable pasture based technologies, such as ley farming, and mixed grass-legume pastures remain unadopted, because their beneficial effects are small relative to the returns that can be captured from speculative land price increases [56]. Technologies improving the pest resistance of the highly productive improved grass pastures are however rapidly adopted. The result is an increase in crop yields and cattle stocking rates (Table 5). There is, however, little incentive to adopt technologies which reduce externalities, such as sedimentation and pollution of water courses, because of the lack of environmental policies and appropriate institutional mechanisms. Technologies such as plantation forestry, fruit and nut trees, and agrosilvopastoral systems are developed for remote cropping areas in the cerrado, but fail to be adopted because export corridors maintain the profitability of cropping in frontier areas. Agroforestry technologies are targeted to small scale dairy farmers in riparian areas to replace some of the ecological services of gallery forests, but are not economically viable.

Land use planning studies investigating the consequences of habitat destruction, spatial variability in biodiversity, and identifying critical wathersheds, keystone species and minimum contiguous areas for habitat preservation, and estimating economic values of losses in environmental services are carried out, but fail to improve the environment, because of the lack of political will, and the lack of appropriate institutional mechanisms.

Thus, this scenario illustrates that in an unfavorable policy environment sustainable technology development's contribution to environmental protection is severely limited. This is demonstrated by simulation results in Tables 6 and 7, which show that land use is virtually unchanged between scenarios 1A and 1B. Grain production in the Cerrado, however, is 80% higher than in scenario 1A, and cattle numbers increase by 67%. Carbon emissions in the Cerrado also decline by about 26% due to more intensive pasture management (Table 7).

5.2.4 Scenario 2B

This is the most favorable scenario, combining favorable policy with a technology development strategy oriented towards sustainable management of ecosystems.

Production of small holder food crop and pasture plots in the Amazon is intensified and stabilized. The technology is available, and at the same time favorable policies have reduced the availability of new land and speculative demand for pasture land. Also improvement of farm to market roads in already deforested areas have reduced input/output price ratios, making the new technologies economically viable. (Table 3).

This is captured in the model by a decline in the rate at which NE is reconverted, from 0.45% of NE under scenario 1A in 2020, to 0.01% under this scenario. The proportion of NE converted to AG doubles in comparison to scenario 1A, with an increase in permanent agriculture (PA) as opposed to slash and burn (SA), and a decline in the amount of fallow land (ALT) converted to pasture for sale to large scale ranchers. Reflecting this simulation results show that, relative to scenario 1A, the loss

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Sustainable forestry begins to replace selective logging leading to an increase in wood yield to about 65% of the Asian level [57]. This is supported by evidence that since the decline in the deforestation rate, the ratio between potential commercial volume and the real volume harvested has increased from 6 in 1980-1988 to 1 in 1990 [11].Adoption also begins to occur of land use systems which exploit ALT to provide some of the ecological services of primary forests. Examples are agroforestry systems, sustainable forestry, reduced impact logging and non-timber forest products. This is because farm to market roads reduce transport costs.This is consistent with evidence of agriforestry systems in areas of relatively good market access in the Peruvian Amazon [58]. In addition, institutional changes such as participation in carbon markets and biodiversity prospecting deals begins to take place, and this increases the returns to land use systems similar to primary forests, thus enabling local people to capture the returns to providing global environmental services through participation in GEMs (Table 3). This is represented in the model by activity PL on ALT which increases to 500 square km. in comparison to negligible levels under scenario 1A. Rehabilitation (NRH) also occurs on 6.5% of ALT versus 0.15% in scenario 1A (Table 4). Simulation results show little difference in the surface area devoted to ALT. However, in scenarios 1A and 1B ALT consists mainly of degraded and abandoned land. In 2B ALT includes 19 million ha of productive and sustainable land use, such as agrosilvopastoral systems and enriched secondary forests. This contributes to major increases in carbon uptake in comparison with other scenarios. These changes enable the Amazon to make a net positive contribution of over 30million t to carbon sequestration by the year 2020 inspite of a doubling in wood production (Table 6).Estimates of damages to the global economy due to global warming range from $1.8/t C to $66/t C [59]. Using one of the latest estimates [60] of $20/t C indicates that carbon sequestration by the Amazon under scenario 2B in 2020 is worth $0.7 billion .

In the Cerrado the profitability of capital intensive crops such as soybean declines in remote areas due to the lack of export corridors. As a result farmers in these areas become more receptive to plantation forestry, fruit and nut trees, and ley farming systems. Adoption of these systems, as well as of reforestation technologies in riparian areas, is also assisted by participation in international carbon markets, while protection of reserves for preservation of natural habitat is improved through biodiversity prospecting deals and ecotourism.

In Cerrado areas closer to markets, profitability of cropping increases both due to macro stabilization and lower interest rates, as well as the adoption of technologies for reducing on-site degradation (Table 3). Technologies for reducing off-site degradation are also now adopted. This is due both to institutional mechanisms such as pollution taxes, as well as to technologies developed collaboratively between the private and public sector. An example is commercial biocontrol, which offers income opportunities for agribusiness, and is therefore likely to be successfully diffused by the private sector. Although the growth in pasture land slows down in the Cerrado, sustainable technologies, such as mixed grass-legume pastures, are adopted because opportunities for land speculation have declined. As a result, stocking rates increase (Table 5).

The increased profitability of crops in areas close to markets is reflected in the model by a much larger proportion of reconverted NE being planted to crops and by an increase in crop yields to over 3 tons/ha (Table 5), resulting a threefold increase in crop production compared to scenario 1A (Table 7). The adoption of tree crop systems is reflected in major increases in the proportion of cleared land going to plantations (PT), and increased rehabilitation activities on ALT (Table 5). Surface area in ALT shows little change, but as in the Amazon, it now consists primarily of agroforestry systems, protected areas and productive secondary forests. The adoption of these systems as well as the adoption of grass-legume pastures on 15% of the improved pasture area, increases carbon uptake and enables the cerrado to make a substantial contribution of 53 million t to carbon sequestration, worth $1 billion, by the year 2020. At the same time the increase in production of grain and wood products in comparison to scenario 1A is greater than the combined increase induced by policy or technology alone, while the increase in cattle numbers relative to scenario 1A amply compensates for the decline in the Amazon (Table 7).

Thus this scenario illustrates the synergy between policy and technology. When the right technologies are available in a favorable policy environment, not only is frontier expansion and its negative environmental implications reduced, but also the quality of land use in areas under human intervention shows major improvements, both in terms of production and the environment.

5.2.5 Relative impact of policy and technology

In this section, simulation results are analyzed to quantify the impact of policy relative to technology. Impact of policy is defined as the absolute difference between the average impact of technology under unfavorable and favorable policies:

$$IP = \left| \frac{S^{*1A} + S^{*1B}}{2} - \frac{S^{*2A} + S^{*2B}}{2} \right| \qquad (6)$$

Impact of technology is defined as the absolute difference between the average impact of policy under productivity oriented technologies and under sustainable technologies:

$$IT = \left| \frac{S^{*1A} + S^{*2A}}{2} - \frac{S^{*1B} + S^{*2B}}{2} \right| \qquad (7)$$

where S^{*v} = normalized surface of land use category under scenario v with scenario 1A as the numeraire

Relative impact of policy/technology: $IP/IT = S^{V}/S^{IA}$

The ratios of the impact of policy and technology for each LUC, production and carbon emissions are given in Tables 6 and 7.

Results suggest that the impact of policy is four times greater than the impact of technology on frontier expansion in both the Amazon and the cerrado. Policy is also the dominant force in determining the area under agriculture in the Amazon and the number of cattle. This is primarily because as incentives for speculation are removed, a larger proportion of deforested land is devoted to agriculture at the expense of speculative cattle ranching. Where cattle ranching persists, productivity becomes more important, leading to increases in cattle numbers.

Technology has the greatest relative impact on the area in planted pastures and on the production of grain, cattle and wood in the Cerrado, reflecting the Cerrado's capacity for making a substantial and sustainable contribution to output, and indicating that without sustainable technologies its productive capacity could be seriously jeopardized. Technology also has a greater impact than policy on ALT in both the Amazon and the Cerrado, indicating that without sustainable technologies a large proportion of deforested land is likely to be unproductive or abandoned, even if incentives for speculation are removed. Policy and technology are equally important influences on carbon sequestration. Policies reduce deforestation, and harness the incentives provided by international trade in carbon storage services. Technologies such as reduced impact logging, agroforestry systems and improved pastures provide land use systems which allow productive use of land while simultaneously having favorable impacts on carbon fluxes.

6 Conclusions

The above analysis demonstrates that although many of the government policies that stimulated frontier expansion have now been reversed, the specter of continued deforestation remains. Simulation results indicate that if macroeconomic stabilization policies fail, and if the government gives in to private sector demands for export corridors to the northern Atlantic and Pacific coasts, frontier expansion could reach 61 million ha. in the Amazon and 23 million ha. in the Cerrado by 2020. Contrary to popular belief the relative loss of habitat would be greater in the Cerrado, where only 9.2 million ha. of the natural ecosystem would be left (6% of the total Cerrado area) thus posing a serious threat to Cerrado biodiversity. While the Amazon (represented in the simulation by the Northern Region) would, by contrast still have 275 million ha. of natural habitat (78% of the total area), carbon emissions would more than double by 2020, and deforested areas could seriously disrupt other ecological functions such as nutrient cycling, soil conservation and watershed protection.

The analysis indicates that if favorable policies are followed, reconversion of natural habitat is reduced by 30% in the Amazon, and 64% in the Cerrado by the year 2020. This ameliorates habitat fragmentation, and carbon emissions. Contrary to popular perception, the results indicate that policy induced declines in frontier expansion need not require sacrifices in grain and cattle production. By the year 2020 grain production in both ecosystems is well above the level under poor policies, because of the increase in crop area, resulting from better economic conditions, and growth in the proportion of cleared area devoted to agriculture. While expansion in pasture area declines, cattle numbers are maintained because of more intensive grazing, resulting from declines in speculative land acquisition.

Results suggest that incorporation of environmental concerns in technology development strategies has minimal impact on frontier expansion if policies remain unfavorable, particularly in the Amazon. In the Cerrado, while resource management technologies reduce on-site degradation and result in increased grain and cattle production and reduced carbon emissions, there is little adoption of technologies for ameliorating off-site degradation (an area of research where the need for public sector involvement is greatest, given that the Cerrado consists predominantly of large scale farmers). Thus policy improvements appear to be a pre-condition for achieving high returns to investment in technology development by the public sector, particularly in the Amazon.

While policy changes alone are highly effective in controlling frontier expansion, on- and off-site resource degradation remains widespread and yields and profits decline in areas already under human intervention if resource management technologies are not developed. In the long run this could have serious repercussions particularly in the Cerrado, which currently provides a third of Brazil's soybean and cattle, and where the intervened area is simulated to be around 143 million ha. by 2020, even if policy changes slow down frontier expansion. In the Amazon, by contrast the intervened area is simulated to be less than 60 million ha. by 2020 under favorable policies, and grain and cattle production is less than 20% of the level in the cerrado. Thus while policies appear to be the top priority in the Amazon, both policies and technologies have a vital role to play in the Cerrado.

Under the best scenario, combining favorable policies and technologies, simulation results indicate a synergistic effect in both ecosystems, with improvements in production (with the exception of cattle) and in the environment (including carbon sequestration worth $1.7 billion/year) being larger than the sum of policy or technology alone. Key elements of successful policies and technologies are identified in scenarios 2A and 1B respectively.

Economic policies in Brazil are already moving towards the best scenario, although social security reform remains a major obstacle to achieving fiscal balance, and unemployment particularly among the poor remains high. Greater political commitment to environmental improvement is however required. Given the powerful soybean lobby, the probability of export corridors cutting through the Amazon remains high. Also, unlike countries such as Costa Rica, there is little government support for participation in global environmental markets. On technology development, major changes in orientation have been achieved, although funding uncertainties cloud the picture. The activities of the national agricultural research system (EMBRAPA) now include land use planning, conservation technologies, and characterization and preservation of native species [61]. Thus, with further improvements in government policy there may be a major opportunity for reconciling growth and environmental protection.

The above exercise has integrated knowledge from diverse scientific disciplines to provide broad indications of the impact of policy and technology on the Amazon and the cerrado. While the results are expected to contribute to policy decisions and the setting of research priorities, it is hoped that they will also stimulate disciplinary scientists to improve the quantification of the cause-effect relationships underlying land use change, thus progressively refining the relevance and reliability of integrated exercises.

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Table 1. Surfaces of land use categories in the Amazon (Northern Region) and Cerrado ecosystems, Brazil.

Land Use Category	Amazon[1]			Cerrado[2]		
	1970	1980	1985	1970	1980	1985
	million ha					
Natural	342.7	335.8	329.5	57.75	32.5	24.36
Agriculture	1.4	2.0	2.0	2.63	5.3	6.93
Pastures	3.4	7.8	10.3	75.23	89.7	93.03
Plantations	0	0.2	0.25	0.63[3]	1.6[3]	3.15[3]
Altered	2.5	4.4	7.8	25.88	32.2	33.6
Urban	0.05	0.1	0.15	0.32	0.7	0.84
Wasteland	0	0	0	0.32	0.7	0.84
TOTAL	350	350	350	162.7	162.7	162.7

1 Sources: INPE [62], Fernside [63], Lanly [57], World Bank [16].

2 Sources: Mueller et al. [1], Lanly [57], Winograd [50].

3 Includes grazed native savanna and planted pasture. Planted pasture (million ha): 9.14 in 1970, 27.8 in 1980, 32.45 in 1985.

Table 2. *Grain yields, cattle stocking rates and wood production: Amazon (Northern Region) and Cerrado ecosystems, Brazil*[1].

Grain yield[2] **(t/ha)**	**Amazon**		**Cerrado**	
Rice	1.1		0.9	
Beans	0.6		0.7	
Soybean	n/a		1.5	
Maize	0.8		1.95	
Cattle	**1970**	**1990**	**1970**	**1985**
Animal units/ha pasture	0.5	0.55	0.22	0.43
Animal units/ha planted pasture	n/a	n/a	1.9	1.22
Heads of cattle (millions)	1.7	9	16	38
Wood Production[3] (Million cubic meters)				
Fuel wood and charcoal	16.5		29.9	
Industrial Round wood	19.8		3.8	

1 Sources: Amazon: Nascimento and Homma [4], Mueller et al. [1]
Cerrado: Mueller et al. [1], Lanly [57], World Resources Institute [64]

2 1990

3 1980-1985

n/a = not available.

Table 3. Impact of scenarios on determinants of frontier expansion, production and the environment: Amazon (Northern Region) and Cerrado ecosystems, Brazil.

Scenario Characteristics	Scenarios							
	1A		2A		1B		2B	
1	Unfavorable		Favorable		Unfavorable		Favorable	
2	Yes		No		Yes		No	
3	No		Yes		No		Yes	
4	No		No		Yes		Yes	
5	High		Low		High		Low	
6	No		Yes		No		Yes	
7	No		Yes		No		Yes	
8	No		No		Yes		Yes	
9	No		No		Yes		Yes	
10	No		No		Yes		Yes	
Impact on	**Amazon**	**Cerrado**	**Amazon**	**Cerrado**	**Amazon**	**Cerrado**	**Amazon**	**Cerrado**
Speculative land	1(+)	1(+)	1(-)	1(-)	1(+)	1(+)	1(-)	1(-)
acquisition	2(+)	2(+)	2(-)	2(-)	2(+)	2(+)	2(-)	2(-)
Amazon:	3(+)		1(-)				3(-)	
migration by poor	2(+)	2(+)	3(-)	2(-)	2(+)	2(+)	1(-)	2(-)
Cerrado:			2(-)		3(+)		2(-)	
demand for frontier crop land								
Production	2(+)	4(-)	2(-)	5(+)	2(+)	4(+)	2(-)	1(+)
	1(+)	5(-)	4(-)	4(-)	1(+)	5(-)	4(+)	5(+)
	8(-)	1,2(+)		7(-)		1,2(+)	6(+)	4(+)
	6(-)	8(-)				8(+)	9(+)	9(+)
Environment	2(-)	2(-)	2(+)	2(+)	2(-)	2(+)	9(+)	7(+)
		4(-)		4(-)		4(+): on site	7(+)	4(+)
						4(-): off site	2(+)	10(+)

1 = macro-economic conditions; 2 = penetration roads/export corridor; 3 = employment opportunities; 4 = integrated pest/nutrient management technologies; 5 = interest rates; 6 = farm to market roads; 7 = institutional mechanisms for externalities; 8 = sustainable pasture technologies; 9 = sustainable forestry/agroforestry technologies; 10 = land use planning.

Table 4. Selected parameters in land use simulation model, by scenario: Amazon (Northern Region) ecosystem, Brazil.

Activities on and flows between Land Use Categories	Selected starting parameters	Selected parameters by scenario (2020)			
	(1980)	1A	2A	1B	2B
Act. RC on NE (% NE)	0.41	0.45	0.1	0.44	0.01
% reconverted NE ⇨ GR	55.45	55.45	50	30	10
% ranch area in GR ⇨ ALT	8.5	8.5	6.5	5.5	4.0
% reconverted NE ⇨ AG	44.3	44.3	49.5	69.5	89.25
Act. FE on NE (% NE)	0.05	0.10	0.06	0.10	0.45
Act. PA on AG (% AG)	5	5	35	16.5	50
Act. SA on AG (% AG)	85	85	55	72.5	40
Act. RC on ALT (% ALT)	9.75	17.75	37	17.75	18.75
% reconverted ALT ⇨ GR	92	92	60	65	7.5
Act. PL on ALT (km^2)	10	10	100	175	500
Act. NRH on ALT (% ALT)	0.15	0.15	0.60	0.15	6.5
Grain yield (t/ha)	0.8	1	0.85	1	1.5
Stocking rate (animals/ha)	0.5	0.7	1.1	1.2	1.6
Wood yield (cubic meters/ha)	12.5	12.5	12.5	12.5	25

Definitions of Activities and Land Use Categories in Figure 2.

Table 5. Selected parameters in land use simulation model, by scenario: Cerrado ecosystem, Brazil.

Activities on and flows between Land Use Categories	Selected starting parameters	Selected parameters by scenario (2020)			
	(1980)	1A	2A	1B	2B
Act. RC on NE (% NE)	2.8	2.20	0.04	1.8	0.01
% reconverted NE ⇨ GR	88.5	88	69	86.5	67
% ranch area in GR ⇨ ALT	6	6	6	6	6
% reconverted NE ⇨ AG	10	10.5	25.5	11	28.5
Activity FE on NE (% NE)	0.75	0.75	0.6	0.4	0.05
% reconverted NE ⇨ PT	1.5	1.5	5.5	2.5	4.5
Grain yield (t/ha)	1.5	1.5	1.5	2.25	3.12
Stocking rate (animals/ha)	0.35	0.5	0.8	0.9	1.1
Wood yield (cubic meters/ha)	12.5	12.5	12.5	12.5	25

Definitions of Activities and Land Use Categories in Figure 2.

Table 6. Simulation results by scenario: surfaces of selected land use categories, production and carbon emissions, relative impact of policy and technology: Amazon (Northern Region) ecosystem Brazil.

	Starting value (1980)	Results by scenario (2020)				Impact of policy relative to tech. (2020)
		1A	2A	1B	2B	
Land Use Category (million ha)						
Natural	335.8	274.5	293.0	278.8	297.0	4.42
Agriculture	2.0	3.0	8.6	4.2	10.3	4.03
Pastures	7.8	48.5	36.4	43.5	16.6	1.57
Plantations	0.2	0.3	0.9	0.7	1.3	1.50
Altered	4.4	23.1	10.6	22.1	24.6	0.77
Production						
Grain (million t)	1.6	3.0	7.31	4.2	15.45	1.67
Cattle (million heads)	3.9	33.95	40	52.2	26.56	4.07
Logs (million cubic meters)	19.8	113	52	125	275	0.38
Net carbon emissions (million t)	101.79	275.6	200.3	252.3	-36.6	1.40

Table 7. Simulation results by scenario: surfaces of selected land use categories, production and carbon emissions, relative impact of policy and technology: Cerrado ecosystem Brazil.

	Starting value (1980)	Results by scenario (2020) 1A	2A	1B	2B	Impact of policy relative to tech. (2020)
Land Use Category (million ha)						
Natural	32.5	9.2	24.1	10.8	30.0	4.55
Agriculture	5.3	7.6	10.3	9.2	13.6	1.45
Pastures (total)	89.7	111.2	95.8	103.4	78.1	1.6
Planted pastures	27.8	39.3	33.5	53.2	54.4	0.13
Plantations	1.6	4.1	5.9	4.7	10.4	1.47
Altered	32.2	26.0	29.0	29.9	26.5	0.29
Production						
Grain (million t)	7.95	11.4	15.45	20.7	42.43	0.71
Cattle (million heads)	31.4	55.6	76.64	93.06	85.9	0.30
Logs, fuelwood, charcoal (million cubic meters)	37.3	30.0	36	57	85	0.45
Net carbon emissions (million t)	70.5	69.6	46.5	51.5	-53.2	1.06

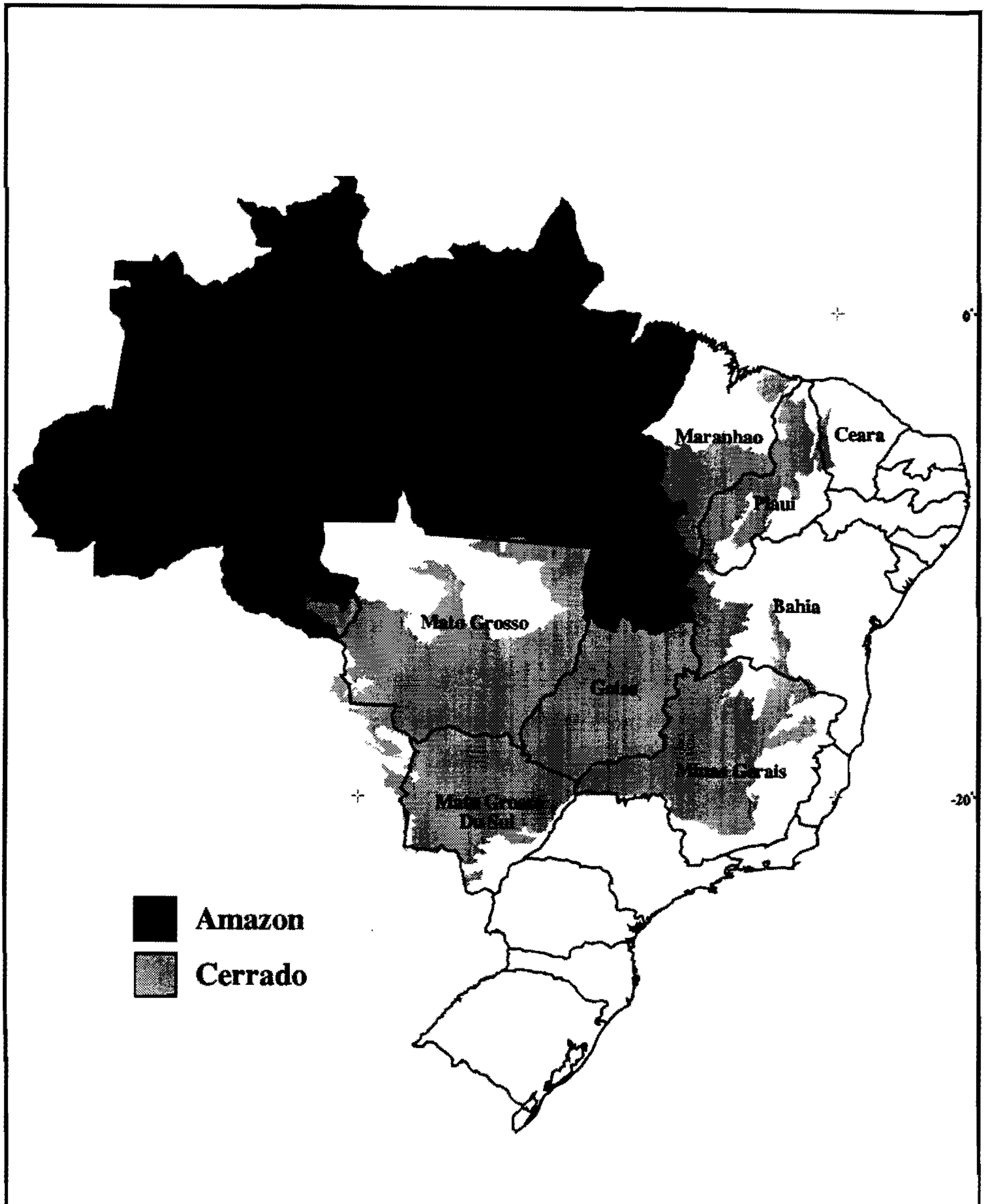
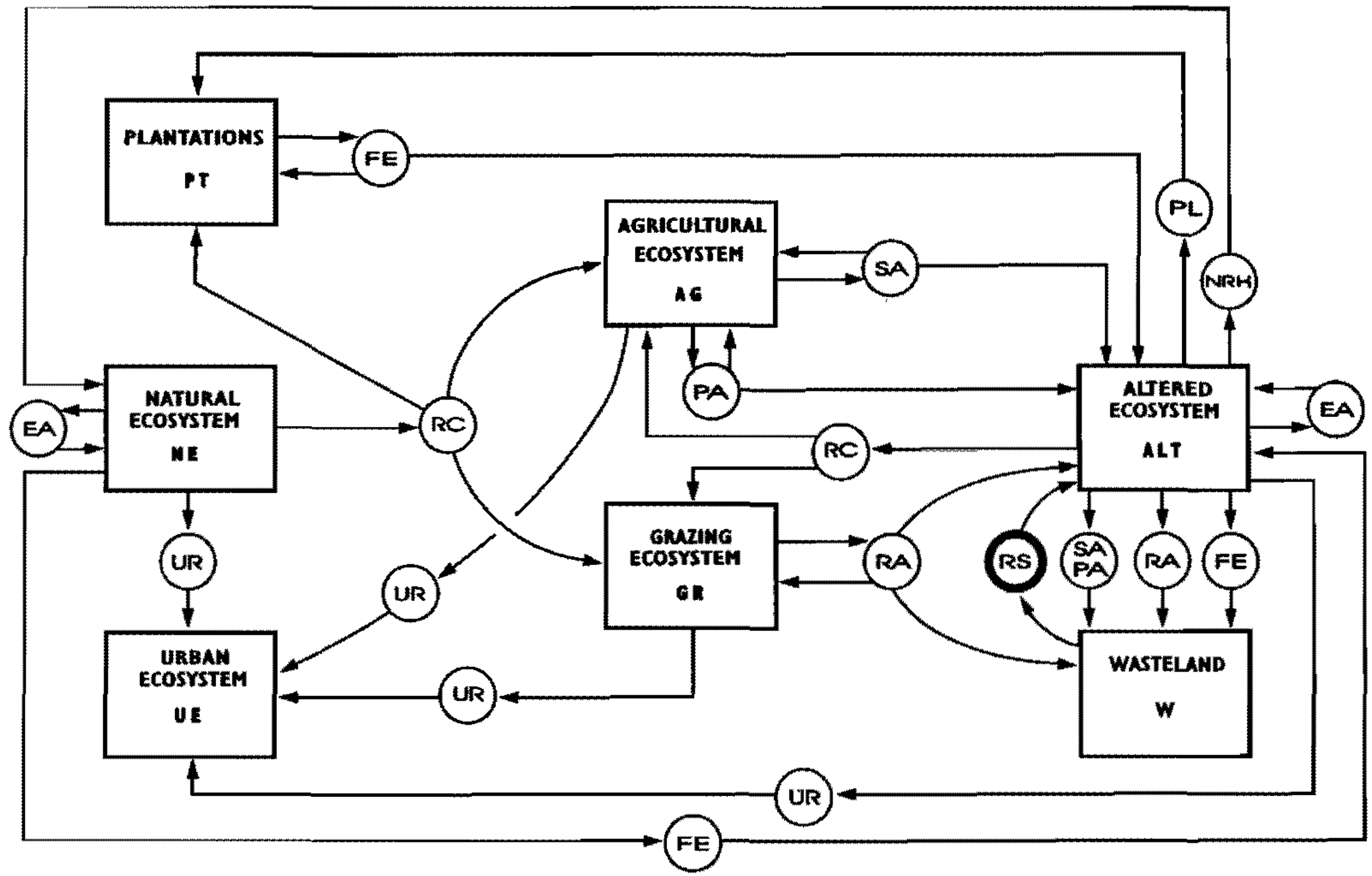


Figure 1: Amazon and Cerrado ecosystems, Brazil

Figure 2. Flow chart of land use model.



Boxes indicate land use categories; circles indicate processes generating transformations. SA = shifting agriculture; PA = permanent agriculture; FE = forest exploitation; EA = extractive activities; RA = ranching; PL = plantations; RC = reconversion; NRH = natural regeneration/rehabilitation; RS = restoration; UR = urbanization.