Environment and Development Economics 10: 485–511 © 2005 Cambridge University Press
doi:10.1017/S1355770X05002305 Printed in the United Kingdom

Inter-regional innovation in Brazilian agriculture and deforestation in the Amazon: income and environment in the balance

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ABSTRACT. The paper examines how recent trends in agricultural productivity in Brazil, occurring both inside and outside the Amazon, affected deforestation and agricultural incomes. The analysis uses a computable general equilibrium model adapted to capture regional economic structures, and accounts for uncertainty concerning productivity improvements. Due to countervailing effects on deforestation of innovation inside and outside the Amazon – respectively, increasing and decreasing it – innovation in Brazilian agriculture in the period from 1985 to 1995 has not altered substantially deforestation rates. However, innovation inside the Amazon has to be reckoned as a driving force behind the continuing high levels of deforestation rates.

Innovation rates for livestock activities, inside and outside the Amazon, prove crucial in determining deforestation and agricultural income. Technological improvements outside the Amazon for small farm production systems and for farms in general in the North-East increase agricultural income, improve income distribution, and limit deforestation rates.

Introduction

Starting in the late 1980s, the Brazilian economy undertook a process of substant restructuring, following dramatic changes in economic policy. The transition, which had considerable repercussions on agriculture, was characterized in its early phase by trade liberalization, deregulation of domestic markets, and privatization of state enterprises. This was followed by the *Real* macroeconomic stabilization plan after macroeconomic events and failed stabilization schemes during most of the 1980s had resulted in instability for the agricultural sector. Another set of policy reforms directly affected the agricultural sector through several avenues: (i) a significant reduction in publicly funded rural credit; (ii) the deregulation of the domestic markets of coffee, wheat, sugarcane, and milk; and (iii) the reduction of support price policies through the elimination of government purchases at a guaranteed minimum price.

Helfand and Rezende (2001) provide an insightful description of the impact of this set of policy reforms on the structure of Brazilian agriculture. One of their conclusions is that, despite the instability brought about by a decade of macroeconomic failures, policy reforms favored improvements in resource allocation, productivity, and product quality, primarily by exposing domestic production to greater competition.

The productivity gains that developed at a sectoral level during 1985 to 1995 could, following Helfand and Rezende (2001), be distinguished conceptually into: (i) gains from technological change, expressed as shift of the production possibility frontier; (ii) scale effects, whereby increased productivity is the result of changes in the scale of operation for a given technology; or (iii) efficiency gains as embodied by movements toward the frontier of a given technology. The authors express their view that, due to increased competition, gains in efficiency have been an important source of the increases in productivity, as the least productive farmers are forced to opt out of activities that are no longer profitable. However, they point out that technological and scale effects also contributed to productivity gains, especially in the Center-West. In addition, throughout Brazil there are indications that modernization of poultry and pig farming is occurring along with a shift from natural to planted pastures for beef production (IBGE, 1998). The Empresa Brasileira de Pesquisa Agropecuária (Embrapa), Brazil's public agricultural research institution, played a pivotal role in the development of new technologies. Improved productivity, policy reform, and publicly funded technological innovation together played an important role in determining Brazil's new agricultural structure, impacting both agricultural incomes and environmental conditions.

The premise of this paper is that the evolution of agricultural productivity, to the extent that it is influenced by the changing policy regime and technological innovation, is an indicator of the underlying forces that affect the demand for factors of production in rural areas. Although it is important to understand the link between policy reform and agricultural productivity, the focus from here on will be on productivity gains in agriculture, independently of the policies that generated them. In this respect, past modifications in agricultural productivity in the South and South-East of Brazil are often invoked to explain rural out-migration from those areas beginning in the 1960s. Similarly, more recent technological improvements in the production of grains in the Center-West, reportedly displaced livestock producers from that region, who moved their livestock operations to Amazon frontier areas (Schneider, 1995). Productivity improvements during 1985–1995 will be used in the paper as a baseline for our projections of future improvements, implicitly assuming that current trends in technological innovation and policy reform will continue. Counterfactual simulations are also presented to highlight what might happen if things take a different turn.

Table 1 presents regional total factor productivity (TFP) gains obtained over the 1985–1995 period, showing that all regions experienced substantial productivity improvements during this time. These estimates were computed based on data provided in Gasques and Conceição (2000) for the 1985–1995 period. In relative terms, the greatest overall productivity improvements occurred in the mid-west (54 per cent), followed by the Amazon (30 per cent), the northeast (24 per cent), and the south/southeast

Table 1. *Total factor productivity improvements in regional agriculture: 1985–1995*

	Overall TFP change in agriculture (%)
Amazon	29.6
North-East	24.2
Center-West	54.2
South/South-East	21.6
Brazil	26.1

Source: Adapted by the author from Gasques and Conceição, 2000.

(22 per cent). Given the premise that substantial productivity improvements in agriculture have occurred in all regions of Brazil, we investigate the impacts that different forms of productivity improvement might have on deforestation and income distribution. The range of possibilities, in terms of productivity improvement, will be determined by a combination of what activities involved innovation (annuals, perennials, livestock), where the innovation occurs, and the factor biases involved.

Different farming and cattle-raising systems have been analyzed for the impact of technological change on deforestation and income occurring in specific areas in the Amazon basin (Cattaneo, 2001; Vosti *et al.*, 2001; White *et al.*, 2001; Toniolo and Uhl, 1995; Mattos and Uhl, 1994). Although the proximate causes of deforestation that have been analyzed in these studies are clearly important, processes outside the region may play a role. In this respect, there is little research addressing the impact on deforestation and income distribution of productivity improvements occurring in Brazil outside the Amazon region.

This paper is a first step in understanding the underlying, less proximate, causes of deforestation and the tradeoffs involved when the level of analysis is broader than just the Amazon. The analysis builds on previous work on the impact of technological change by Coxhead and Warr (1991), Coxhead and Jayasuriya (1994), and Jayasuriya (2001). These authors, who focused on countries in tropical Asia, highlight the importance of distinguishing where innovation occurs, since land resources cannot migrate, and the role of factor biases in determining deforestation and income distribution. Besides the geographic focus on the Brazilian Amazon, this paper also presents methodological differences compared with previous contributions. First, we rely on historical data to represent the relative magnitude of productivity improvements in different areas (as opposed to performing hypothetical counterfactuals). In addition, Monte Carlo simulations obtained using a multi-regional CGE model of Brazil are carried out to characterize the uncertainty concerning productivity improvements in agriculture and the impact they may have on deforestation in the Amazon and income distribution in Brazil.

Our incorporation of uncertainty and how the results are presented were inspired by Abler *et al.* (1999), who addressed parameter uncertainty in the context of the environmental impacts of economic policies in Costa Rica. The focus of this paper is slightly different, to the extent that we concentrate on the uncertainty surrounding the scenarios to be simulated, rather than that concerning the parameters of the model used.[1]

The paper is structured as follows. The first section clarifies the modeling strategy considered appropriate for understanding how productivity improvements affect deforestation, and briefly describes the database adopted. Section 2 then presents the simulation scenarios for productivity improvements and considers the uncertainty surrounding the scenarios. In section 3, the impact of productivity improvements on deforestation and agricultural incomes are presented. Results are structured so as to show separately the contribution of innovation in agriculture inside and outside the Amazon.

1. Model characteristics

The starting point for the development of this model is a standard CGE model as described in Dervis *et al*. (1982), and the structure of the model draws most directly on Robinson (1990). Several innovations were introduced to make it suitable for analyzing issues pertaining to deforestation in the Brazilian Amazon. The model builds on the approach introduced by Persson and Munasinghe (1995) for a study of Costa Rica. They include logging and squatter sectors and therefore markets for logs and cleared land. We extend their approach to consider: (i) the migration process to frontier areas using econometric estimates, (ii) the link between logging and deforestation for agricultural land clearing, and (iii) land degradation as a feedback mechanism into the deforestation process. In the modeling approach adopted here, a regionalized CGE model is developed in which Brazil is subdivided into four regions compatible with the major administrative subdivisions adopted by the Brazilian government: Amazon, North-East, Center-West, and South/South-East.[2]

The activities considered in the model are presented in table 2, along with the factors employed in production and the commodities being produced by these activities.

Agricultural production is disaggregated by region (Amazon, Center-West, North-East, South/South-East), by activities (annuals, perennials, animal products, forest products, and other agriculture), and, by size of operations (smallholder, large farm enterprise). Regional agricultural producers sell their products to a national commodity market. Households are specified at the national level and are disaggregated into five categories: urban low income, rural low income, urban medium income, rural medium income, and high income.

The primary factors of production are capital, labor, and land, which are disaggregated into different categories. Capital is classified as rural or

[1] In our case, a preliminary sensitivity analysis indicated that the impact of parameter uncertainty for model elasticities was secondary relative to the impact of scenario uncertainty concerning technological change.

[2] The specification of the Amazon deviates from administrative boundaries because it is meant to include only economic activities on land that is still forested or along the arc of deforestation. The boundary description relies on data provided by Alves (2001) and is described in Cattaneo (2002).

Table 2. *Mapping of economic activities to commodities produced and factors used (as adopted in the model)*

Activity	*Commodities produced*	*Factors used*
Annuals production	Corn, rice, beans, mandioca, sugar, soy, horticultural goods, and other annuals	Arable land, unskilled rural labor, skilled rural labor, agricultural capital
Perennials production	Coffee, cacau, other perennials	Arable land, unskilled rural labor, skilled rural labor, agricultural capital
Animal products	Milk, livestock, poultry	Grassland, unskilled rural labor, skilled rural labor, agricultural capital
Forest products	Non-timber tree products, timber, and deforested land for agricultural purposes	Forest land, unskilled rural labor, skilled rural labor, agricultural capital
Other agriculture	Other agriculture	Arable land, unskilled rural labor, skilled rural labor, agricultural capital
Food processing	Food processing	Urban skilled labor, urban unskilled labor, urban capital
Mining & oil	Mining & oil	
Industry	Industry	
Construction	Construction	
Trade & transp.	Trade & transportation	
Services	Services	

urban, based on the activities adopting it. Labor is categorized as skilled or unskilled, and as rural or urban resulting in four labor categories. Land is used by the four agricultural activities and in producing forest products. Land is differentiated into *land types*, on the basis of cover, into the following categories: forested land, arable land, grassland/pasture, and degraded land (not productive). All factors employed by agriculture are region-specific. Labor is inter-sectorally mobile and can migrate between rural regions and to the urban sectors, whereas capital funds can move between sectors and regions, but with the assumption that the capital market is segmented into rural and urban without movement between the two.[3] Capital is further segmented in rural areas into large farm capital and smallholder capital, implicitly assuming that small and large farms are competing for different pools of funds. For factors in general, allowing for mobility does not eliminate all differences in factor prices between sectors. Rather, the ratio of the sectoral factor supply price to the economy-wide average supply price of that factor remains constant through factor mobility.

[3] Capital markets are segmented because the simulation does not include productivity increases in industry. Given the size of the urban/industrial sector, if capital were allowed to move from urban to rural it would be as if agriculture were unconstrained on the capital side. On the labor side, we allow labor to move to urban areas in case productivity improvements displace labor.

The total demand for each of the 24 goods is the sum of exports, domestic consumer demand, government demand, investment demand by firms, and intermediate demand in production. The quantity of each good exported is a constant elasticity of function of its world price. Consumer demand, investment demand, and government demand are constant budget shares across the commodities demanded. The economy's total supply of each good is the sum of non-exported production and imports, with the quantity of each imported good being a constant elasticity function of its world price. Market equilibrium is assumed, so total supply equals total demand for each good.

To complete the model, we define closure rules describing how the major macroeconomic accounts adjust to regain economic equilibrium in response to changes in economic activity. In our case, the real exchange rate, which is defined here as the nominal rate divided by the domestic price index, adjusts so as to maintain a constant current external account. Government and investment spending are a fixed share of the sum of final demand expenditures.

The subsections that follow illustrate some specific features of the model that are necessary for a meaningful analysis of the impact of productivity improvements. Without going into the details of the model, we describe the approach taken in considering migration, modeling land use change, and representing the agricultural production process.[4]

Modeling migration

To consider migration mechanisms, one must identify the determinants of internal migration in Brazil. At the aggregate level, several studies were carried out during the 1960s and 1970s that attempted to relate regional and sectoral wage differentials and internal migration. Sahota (1968) and Graham and Buarque de Holanda (1971) measured the responsiveness of migration to differentials in earnings and other variables. A number of studies, reported in Martine (1990), analyzing migration at a more local level, have shown that a broad mixture of 'push' and 'pull' factors is necessary to explain the decision to migrate. However, as Martine points out, both aggregate and local survey data show the predominance of economic motives of migration in Brazil.

Despite the body of work developed in the 1960s and 1970s, there is almost no recent literature on internal migration in Brazil. The exceptions to this rule are Perz (2000) and a survey by SENAR/FGV (1998), both investigating the propensity to migrate to urban areas, but no attention is paid to rural–rural migration or to modeling the economic determinants of migration. Since the research presented here focuses on the economic determinants of migration to the agricultural frontier, wage differential threshold parameters were used to characterize migration mechanisms. The threshold parameters were estimated using data on inter-regional wage differentials and migration from one rural area to another and between rural and urban areas.

The wage differential threshold parameter indicates how much the relative inter-regional wage differential for a factor must shift between two

[4] A detailed description of the model can be found in Cattaneo (2001 and 2002).

https://doi.org/10.1017/S1355770X05002305 Published online by Cambridge University Press

Table 3. *Intra-regional migration estimation results: wage differential threshold (%) before movement occurs between two regions*

	Migrant destination				
Migrant origin	*Urban unskilled labor*	*Amazon agr. unsk. labor*	*North-East agr. unsk. labor*	*Center-West agr. unsk. labor*	*South/South-East agr. unsk. labor*
Amazon agr. unsk. labor	7.7				
North-East agr. unsk. labor	7.1	19.4		15.1	8.6
Center-West agr. unsk. labor	7.9	5.5			
South/South-East agr. unsk. labor	7.6	13.9		7.4	

regions before migration from one region to the other begins to occur. The principle behind this approach is that migration to certain regions may be preferred over others. The estimation of these thresholds captures a diverse set of motivations that may affect the decision to migrate, such as the risk involved in moving to an area, family support networks in the receiving region, or simply climate and infrastructure conditions of the receiving region relative to the area of origin.[5]

To estimate the parameters, a cross-entropy estimation method is adopted as presented in Golan *et al.* (1996).[6] As might be expected, the threshold wage differential for migration to urban areas is lower than for rural to rural migration, indicating a greater propensity to migrate to urban areas (table 3). What also emerges is that migrants from the North-East make strong distinctions among rural regions of destination: the preferred migration options being the South/South-East and the Center-West. The Amazon is the last choice as a destination for North-Eastern migrants, requiring a 20 per cent wage differential before migration along this route begins to occur. Interestingly, the Amazon is the preferred destination for migrants from the sparsely populated Center-West, where migrants require a wage differential threshold of only 5.5 per cent. This may be a reflection of the fact that the Center-West is attracting migrants from the South/South-East and the North-East, and in the process farmers in the Center-West are selling out and moving to the nearby agricultural frontier in the Amazon. These regional differences in migration patterns can have a considerable impact on the ability of regions where agriculture is restructuring to attract labor if required. In this respect, it is an important element in determining land use change that results from productivity improvements.

[5] For the purpose of the threshold parameters estimation, it is assumed that migration between two regions is described by a piecewise-linear relationship between the inter-regional wage differential and the number of people migrating.

[6] See Cattaneo (2002) for details on the estimation and its results.

https://doi.org/10.1017/S1355770X05002305 Published online by Cambridge University Press

Modeling land use change: economic and biophysical processes

Land degradation processes are assumed to affect farmers' incentives to deforest to the extent that they impact profitability of activities and the land stocks available to carry out such activities. Land has different qualitative characteristics, which are perceived as distinct by economic agents; these characteristics identify types of inputs into the production functions. As mentioned previously, land is differentiated in land types on the basis of cover into the following categories: (i) forested land, (ii) arable land, (iii) grassland/pasture, and (iv) degraded land. *Land Transformation* is defined as a transition between land types due to physical processes, given certain economic uses. The literature reports that it takes 2–4 years for the transition from arable land to grassland under annuals, and 8–15 years to go from grassland under pasture to degraded land that is either abandoned or left fallow (Vosti *et al.*, 2001; Vosti *et al.*, 2002; Fearnside, 1997; Weinhold, 1999).[7] *Land Conversion* describes a transition between two land types brought about intentionally by economic agents. In the simulations presented below, we allow for (i) farmers clearing forest to obtain arable land and (ii) farmers using arable land for pasture.

The incentives to convert land from one type to another are driven by the returns accruing to each category and the time horizon over which they can accrue. For deforestation, this will depend on the differential in returns between arable land and forested land and on the fact that, depending on the activity undertaken on newly deforested areas, degradation may occur, thereby affecting the stock of land. The price for arable land is determined by the returns to agricultural land, taking into account land degradation.

The amount of land that will be deforested will depend on the price of arable land and on the deforesters' profit-maximizing behavior and technology. The behavior of agents carrying out the land clearing can be differentiated according to whether forest is an open-access resource, or whether property rights governing the use of the forest resource are well-defined. For a more detailed explanation of the approach taken, we refer the reader to Cattaneo (2002).

Modeling the agricultural production process

The specification of multi-output production functions in the CGE model allows for the possibility that farmers consider certain agricultural commodities as substitutes, and others as complements, in the production process. We allow for multiple outputs for any given activity by having agricultural technologies by sector specified as two-level production functions assuming separability between the two levels. At the lower level, real value added is a constant elasticity of substitution (CES) function of the primary factors of production; output by activity is a fixed-coefficients function of real value added and intermediate inputs. Data on regional factor intensities and input use for selected activities were provided by Embrapa. The output of the agricultural activity is

[7] Here a conservative estimate was adopted of three years for transition from arable land to grassland under annuals and eight years from grassland under pasture to degraded land. See Cattaneo (2002) for more details.

Table 4. *Production technology: substitutability between agricultural commodities*

Technology	*Commodity 1*	*Commodity 2*	*Substitutability*
Annuals production	Corn	Rice, beans	Low
	Corn	Mandioca	Low–medium
	Corn	Sugar, soy, horticulture, other annuals	Medium–high
	Rice	Beans	Low
	Rice	Mandioca	Low–medium
	Rice	Sugar, soy, horticulture, other annuals	Medium–high
	Beans	Mandioca	Low–medium
	Beans	Sugar, soy, horticulture, other annuals	Medium–high
	Mandioca	Sugar, soy, horticulture, other annuals	Medium
	Sugar	Soy, horticulture, other annuals	High
	Horticultural goods	Other annuals	Medium–high
Perennials production	Coffee	Cacau	High
	Coffee	Other perennials	Medium
	Cacau	Other perennials	Medium–high
Animal products	Livestock	Milk	Medium
	Poultry	Livestock, milk	Medium–high
Forest products	Deforested land (agric.)	Timber	Low–medium
	Deforested land (agric.)	Non-timber tree products	High
	Non-timber tree products	Timber	High

Notes: The elasticity ranges are: low = 0.1 to 0.3, low–medium = 0.7 to 0.9, medium = 1.0 to 2.0, medium–high = 2.0 to 4.0, and high = 4.0 to 8.0.

transformed, at the second level, into commodities according to a smooth concave transformation frontier described by a translog function.

Values for the elasticities were obtained by distributing a survey among researchers at Embrapa and the International Food Policy Research Institute (IFPRI) with expert knowledge about the production process in Brazilian agriculture.[8] The results are presented in table 4. High substitutability in production replicates the linear programming farm model approach to production, in shifting production to the most profitable crop. If, alternatively, farmers weigh price signals with other factors when making

[8] The survey was distributed to 16 researchers. Eleven researchers responded. The survey was in a matrix format asking the experts to fill in a qualitative manner what they thought was the substitutability in production between different commodities (possible answers were: low, low-medium, medium, medium-high, high). The results were fairly consistent indicating a consensus in relative substitutability between commodities. Given the qualitative nature of the survey, the results were interpreted and put in relation to existing estimates in the literature.

https://doi.org/10.1017/S1355770X05002305 Published online by Cambridge University Press

this decision, then substitution elasticities are lower. Possible factors being considered were: (i) relative risk associated with the crops, (ii) subsistence requirements, (iii) crops requiring similar soil characteristics (substitutable) or different soil characteristics (less substitutable), (iv) common practice (habit), and (v) whether inter-cropping is common for two crops.

Other data

The data used in this model were drawn from Cattaneo (2002). The original sources used to construct the Social Accounting Matrix were the 1995 IO table for Brazil (IBGE, 1997a), National Accounts (IBGE, 1997b). These sources were integrated with the Agricultural Census data for 1995–1996 (IBGE, 1998) to yield a regionalized representation of agricultural activities. Household data were obtained from the national accounts and the household income and expenditure surveys. Total labor, land, and capital value added were allocated across the agricultural activities, based upon the Agricultural Census. Labor was disaggregated into agricultural and non-agricultural labor, and further differentiated as skilled or unskilled. Gross profits in agriculture were allocated in part to land, based on the return to land being used by the activity (FGV, 1998), and, for the remaining part, to capital.

Regional marketing margins were estimated by calculating the average distance to the closest market, and using the ratio of these values relative to the industrial south to multiply the trade and transportation coefficients of each agricultural sector as obtained from transportation cost surveys (SIFRECA, 1998).

Deforestation in 1995 was assumed to equal average deforestation between 1994 and 1996 (in hectares). The coefficients for deforestation technology were obtained from Vosti *et al.* (2002). Timber production in the Amazon, and in the rest of Brazil, was obtained from the agricultural census. The economic rent to timber was based on a technological specification proposed by Stone (1998). Elasticities of substitution between production factors were taken for industry from Najberg *et al.* (1995).

The CGE model was constructed using the General Algebraic Modeling System (GAMS) and solved using the PATH mixed complementarity solver available in GAMS. The model size was 1,417 variables and 1,417 equations.

2. Incorporating uncertainty concerning productivity improvements

Significant uncertainty exists concerning which activities in Brazilian agriculture experienced productivity improvements, to what extent, and what factors of production were affected. This uncertainty stems in large part from the fact that it is difficult to separate the technological change, scale effects, and efficiency gains as described in the introduction. An additional layer of uncertainty is driven by the fact that it is rarely known which factors' productivity is being improved.

Aggregate estimates of regional productivity improvements for agriculture as a whole have been available for Brazil for the period 1985–1995 (Gasques and Conceição, 2000). However, more information is needed at the sectoral level to perform an analysis of the impacts of productivity improvements on land use and income generation. We therefore construct a

Table 5. *Understanding productivity improvements in Brazilian agriculture 1985–1995: a regional perspective on selected activities*

PASTURE: shift from natural to planted pasture

	Area in 1985 (million hectares)		*Change in Area 1985–1995*	
	Natural	*Planted*	*% change natural*	*% change planted*
Amazon	11.8	9.1	−18.1	61.8
North-East	23.3	11.9	−14.2	2.0
Center-West	29.0	28.0	−39.8	34.7
South/South-East	46.2	22.8	−32.9	20.6
Brazil	110.2	74.0	−29.2	34.6

ANNUALS: per cent increase in yields for 1985–1995

	Maize	*Beans*	*Rice*	*Wheat*	*Soybeans*
Amazon					
North-East					
Center-West	55–67%	20–48%	44–85%	35–63%	28–31%
South/South-East	15–33%	−13–40%	29–61%	53–98%	7–27%
Brazil					

Sources: (i) IBGE, 1998a and (ii) Evenson and Avila, 1995.

scenario that decomposes the aggregate regional productivity improvement into its components in terms of annuals, perennials, and livestock activities. Upper and lower bounds for productivity improvements, to be used in a Monte Carlo simulation running the CGE model, were chosen based on measures of agricultural productivity improvements reported in the literature for the period under consideration. The scenario relies on data from: (i) Gasques and Conceição (2000) for total factor productivity (TFP) in agriculture at the State level, (ii) Evenson and Avila (1995) for annual crop TFP changes in selected states, and (iii) the 1995/96 Agricultural Census for shifts from natural pasture to planted pasture as a proxy for change in the productivity of livestock activities. To obtain the productivity changes with the regional specification adopted in the model, the estimates at the state level were aggregated to the regional level by weighting the productivity change according to the states' share of agricultural land in their respective regions. This resulted in the estimates reported in table 5.

What emerges from the aggregated estimates is that, except for the North-East, all areas had large increases in the area in planted pasture (mostly substituting natural pasture), indicating substantial technological innovation among livestock technologies.[9] The section on annuals in table 5 shows Evenson and Avila's lower and upper estimates of

[9] Gasques and Conceição (2000) also report increasing specialization in poultry in the North-East, and in poultry and swine in parts of the Center-West and South/South-East (which would not be picked up by shifts to planted pasture even though they are livestock activities).

https://doi.org/10.1017/S1355770X05002305 Published online by Cambridge University Press

Table 6. *Replicating productivity improvements for the period 1985–1995: a retrospective scenario*

	Amazon	*North-East*	*Center-West*	*South/South-East*
Small farm				
Annuals	0–10	0–15	0–20	10–30
Perennials	10–30	15–35	0–10	0–20
Animal prod.	30–50	5–20	0–20	10–30
Large farm				
Annuals	0–10	0–15	30–60	20–50
Perennials	0–10	15–35	0–10	0–20
Animal prod.	30–50	0–15	20–50	10–30

Note: numbers represent lower and upper bounds (in percentage terms) of a uniform distribution expressing the cumulative productivity gains that occurred during the period.

productivity improvement for a set of annual crops. One can observe that the Center-West has had consistently high productivity improvements in annuals. Although the South/South-East region had noticeable increases in productivity of annuals, the Center-West, with the exception of wheat, has had greater technological improvement. This is due to the improvements introduced by Embrapa in adapting these crops to the climatic and soil conditions in the 'cerrado' regions of the Center-West.

The data in table 5 were used to construct the upper and lower bounds presented in table 6. The bounds were conceptualized so as to capture the relative changes in technology that occurred from 1985 to 1995. The bounds express the (i) great improvement in the production of annuals among large farms in the Center-West and South/South-East regions, (ii) a considerable improvement in livestock productivity in all four regions, and (iii) productivity improvements in perennials production in the North-East (as reported in an anecdotal manner in Gasques and Conceição, 2000).

The magnitude of the productivity improvements in the Monte Carlo simulation was assumed to follow a univariate uniform distribution defined by the bounds in table 6. The improvements were sampled so as to be consistent with the aggregate regional and national productivity in agriculture and matched the numbers reported in table 1. The simulations reflect that the greatest overall productivity improvements occurred in the Center-West (54 per cent), followed by the Amazon (30 per cent), the North-East (24 per cent), and the South/South-East (22 per cent). In essence, the simulation strives to represent all possible combinations of productivity improvements that would result in the aggregate numbers found in the literature.

Similarly to Cattaneo (2001), this paper assumes innovation in agriculture can take on different forms in terms of what factors are affected (factor bias of productivity improvements). Due to technical difficulties in randomizing which factors receive a boost, simulations were run for a subset of possible combinations of productivity improvements. The results presented here cover only a factor neutral total factor productivity (TFP) improvement, and a land-saving scenario for which labor and capital productivity improve at

https://doi.org/10.1017/S1355770X05002305 Published online by Cambridge University Press

the same pace, requiring less land per unit of output. Limiting the results to these two cases is consistent with results reported by Barros (1999) and, furthermore, represents the extremes encompassing the other forms of productivity improvements.

3. Model results

In this section, we present the results of a probabilistic analysis of the potential tradeoffs between income generation, income distribution, and environmental objectives as they pertain to productivity improvements in Brazilian agriculture. To accomplish this, we used a sample size of $n = 10{,}000$ in each Monte Carlo experiment. This is the number of simulations typically performed in Monte Carlo exercises to guarantee the numerical stability of the tails of the output distribution. The approach guarantees the percentage changes in deforestation and income are estimated with a margin of error of less than 0.1 percentage points with 99 per cent probability. The results report the mean percentage change of deforestation and income, the standard deviation (in parentheses), and the sample probability that a decrease in the variable being considered occurs.

In the following subsections, we first approach the issue of how the overall trends in agricultural innovation impact deforestation and income, and proceed to decompose the contributions of productivity improvements occurring inside and outside the Amazon. The section closes with a discussion focusing on alternative scenarios for potential technological innovation outside the Amazon by analyzing potential changes in productivity trends for small farms, for livestock producers, and producers in the North-East.

A retrospective scenario: impact of recent trends in productivity improvements (1985–1995)

The underlying assumption of this section is that current trends in productivity will continue in the near future, both in terms of Embrapa's research focus and in terms of policy reforms and relative price shifts that stimulated previous productivity improvements. We attempt to shed some light on how, under these conditions, the factor intensities of different agricultural activities, combined with the 'push' and 'pull' effects on factors of production that may arise from factor-specific innovation affect deforestation rates and agricultural income.

Deforestation and technological innovation: a precarious balance

Looking at the impact on deforestation of the type of productivity improvements that occurred during the 1985–1995 period, we observe that deforestation results are sensitive to the factor-intensity of these improvements (table 7). For factor neutral innovation, in which all factors in an innovating sector increase their productivity by the same amount, the overall impact on deforestation is minimal (+2 per cent), and in probability terms deforestation is nearly as likely to decrease (0.43) as to increase (0.57). However, if 'land-saving' innovation improves productivity of labor and capital, without spillovers on the returns to land, the mean of the deforestation rate decreases by 32 per cent. This type of innovation would

Table 7. *Impact on deforestation of different types of productivity improvements inside and outside the Amazon*

	Mean change in deforestation (%)	*Standard deviation*	*Probability that deforestation will decrease*
TFP innovation			
All regions: historical trend	2.15	(7.89)	[0.43]
Amazon historical trend	48.08	(7.96)	[0.00]
Non-Amazon historical trend	−26.64	(3.76)	[1.00]
Land-saving innovation			
All regions: historical trend	−32.04	(5.81)	[1.00]
Amazon historical trend	26.10	(4.72)	[0.00]
Non-Amazon historical trend	−34.92	(4.61)	[1.00]

Note: Results report the mean percentage change of deforestation, the standard deviation (in parentheses), and the sample probability that deforestation decreases [in brackets].

surely contribute to limit deforestation with probability = 1. However it is unlikely that innovation would have no spillovers on the return to land. The 'land-saving' scenario is meant mainly as a lower bound on the impact on deforestation of productivity improvements because it entails lower demand for land for a given output. As a lower bound, it suggests considerable uncertainty surrounds the impact on deforestation of overall historical productivity improvements, given the uncertainty on factor biases of innovation. However, it is unlikely that overall productivity improvements in Brazil taken as a whole caused a major increase in deforestation rates.

Separating sectoral innovation into that occurring inside the Amazon *vs*. that which occurred in the rest of Brazil provides some insight on their relative impact on deforestation. It also suggests why deforestation has not decreased despite the fact that previously identified driving forces, such as subsidies, tax breaks, and development of colonization projects, have been phased out. What is immediately apparent is that the type of innovation that occurred inside the Amazon between 1985 and 1995 tends to unambiguously increase deforestation, while innovation outside of the Amazon tended to decrease it. The conspicuous impact on deforestation of Amazon innovation, at a time when government policies favoring agricultural expansion in the region were being eliminated, presents the possibility that a transition occurred in the Amazon from an agricultural sector that relied on subsidies to one that is competitive. This is consistent with anecdotal evidence that considerable restructuring occurred in the 1990s in Amazon agriculture especially among larger farms.

Understanding the dichotomy between the impacts on deforestation of innovation inside and outside the Amazon also helps understand the source of the uncertainty in determining these impacts. Innovation in the Amazon, by itself, would have caused a 48 per cent increase in deforestation if factor-neutral, but only a 26 per cent increase if 'land-saving'. On the other hand, the impact of innovation outside the Amazon – a reduction in deforestation ranging between 26 per cent (factor-neutral) and 35 per cent (land-saving) – is less sensitive to the factor biases of the productivity improvements.

The difference in sensitivity of deforestation to the factor biases of productivity improvements is linked to the 'push' and 'pull' effects on factors caused by innovation inside and outside the Amazon. Productivity improvements in the Amazon can have a direct impact on the returns to land in the area. If these increase, as in the factor-neutral innovation case, labor and capital will be diverted from other activities so as to clear new land. This is a 'pull' effect and it is very sensitive to the returns to agricultural land in the Amazon. Conversely, although deforestation is affected by productivity improvements occurring outside the Amazon, it is less sensitive to which factors' productivity is increased, and depends more on which sectors are affected and the impact on terms of trade for Amazon products. The effect on deforestation occurs indirectly, through the impact on returns to land associated with a change in the relative price of agricultural commodities. For example, innovation in annuals in the Center-West could spur a movement into annuals and away from livestock in this region, worsening terms of trade for annuals in the other regions of Brazil (including the Amazon) and improving their terms of trade for livestock. Capital and labor employed in livestock activities in the Center-West that would be displaced by the innovation in annuals would then migrate to where the terms of trade are more favorable for livestock. This is a 'push' effect and it is important to note that there are multiple migration pathways that a displaced factor may follow.

In other words, since Amazon innovation creates a 'pull' on factors, the factor bias of productivity improvements matters; on the other hand, the impact of other regions' innovation on the Amazon is mainly through how activities are impacted because of the distributed 'push' of any losing factors. This impact is generally lower, as losing factors can follow many possible migration paths, with the path to the Amazon being simply one among several options. A final point worth noting is that these countervailing 'push' and 'pull' forces do not respond linearly when combined. For example, in the case of factor-neutral TFP innovation, adding the results of innovation inside with those for innovation outside the Amazon, one might expect the net effect to be an increase in deforestation rates. However, the result for factor-neutral simultaneous innovation in all four regions indicates that the two effects cancel out, with nearly equal probability for increase or decrease in deforestation rates, creating a precarious balance.

Income generation and technological innovation: regional winners and losers
From an income generation perspective, if we assume factor-neutral TFP innovation to be the default, the impact of overall historical productivity improvements in agriculture has been negative if aggregated at the national level (−7 per cent).[10] This is not uncommon with productivity

[10] The change in value added if technological change occurring is land-saving is reported in the appendix. This is done to simplify the presentation of the results consistently with the view that TFP improvement is more relevant (since spillovers to

improvements in agriculture, since demand for agricultural commodities often has a very elastic response.

When considering the impact at the national level of the combined productivity improvements inside and outside the Amazon, the price effects counterbalance the higher returns from increased factor productivity. However, the impact on income varies substantially across regions and farm types (table 8). First of all, the negative impact on income at the national level is due mainly to reduced income in the South/South-East (−12 per cent), stemming from declining terms of trade for agricultural producers in the area. Large farms in the South/South-East would be particularly hard hit by competition with the Center-West in the production of grains and livestock.

Small farms appear to perform better under the current trends of productivity improvements in agriculture. In the Amazon and the North-East, small farms are the most favored by historical productivity improvements, gaining on average 4 per cent and 9 per cent respectively.[11] Although small farms in the other two regions are likely to experience a decrease in income, the results suggest that the overall impact in income distribution would be toward reduced inequality. A possible explanation of this phenomenon, besides the greater productivity improvements assumed for perennials on small farms, is that the bundle of goods produced by small farms is more diversified than for large farms, and therefore less subject to swings in the terms of trade.

Decomposing the impact on income of productivity improvements into that driven by innovation inside the Amazon and innovation in the rest of Brazil is relatively straightforward. Amazon innovation leads to greater incomes for Amazon farmers and losses for farmers in other regions in what is essentially a zero-sum result (−0.81 per cent) with the Center-West having the sharpest decrease due to losses in the livestock sector.[12]

If innovation were to occur only outside the Amazon, the income of Amazon establishments would decrease considerably (−22 per cent) as the terms of trade for their products would be negatively affected. However, the increased productivity translates into greater supply and also declining terms of trade for the innovating regions. The income effects in these areas, without technological improvements in the Amazon, resemble a slightly improved version of those presented above for combined innovation inside and outside the Amazon. The exception to this parallel is the performance

return to land are likely to occur). Compared with the TFP case, the results diverge for value added generation in the Center-West and the regional forest sectors, but are otherwise quite similar (in terms of probability of an income increase).

[11] Considering the high standard deviations for the historical innovation, the mean value of change in income only provides an indication of the direction of change. The probability highlights, however, that incomes for small farms in the Amazon and the North-East are the most likely to increase under the type of innovation that occurred during the period 1985–1995.

[12] This result assumes that innovation in the Amazon proceeds, while everywhere else it stops. Therefore, the innovation, particulalry in livestock technologies, favors the Amazon relative to the other regions.

Table 8. *Impact on value added of total factor productivity improvements inside and outside the Amazon*

	All regions innovate			*Amazon only innovation*			*Innovation only outside of the Amazon*		
Amazon									
Small farms	3.64	(8.02)	[0.37]	39.34	(16.22)	[0.00]	−17.83	(1.80)	[1.00]
Large farms	−7.94	(9.11)	[0.79]	26.59	(16.83)	[0.07]	−27.14	(2.06)	[1.00]
Forest activities	−0.28	(7.47)	[0.56]	60.02	(11.24)	[0.00]	−23.38	(2.30)	[1.00]
Sub-total	−0.53	(3.62)	[0.57]	38.11	(2.70)	[0.00]	−21.50	(1.83)	[1.00]
North-East									
Small farms	8.55	(6.59)	[0.10]	−2.94	(0.46)	[1.00]	10.21	(6.84)	[0.06]
Large farms	−10.56	(6.76)	[0.94]	−5.14	(0.81)	[1.00]	−7.58	(6.30)	[0.88]
Forest activities	−0.18	(0.72)	[0.57]	−2.53	(0.39)	[1.00]	0.51	(0.39)	[0.10]
Sub-total	1.65	(3.43)	[0.33]	−3.68	(0.55)	[1.00]	3.72	(3.64)	[0.16]
Center-West									
Small farms	−3.41	(13.51)	[0.67]	−11.05	(0.86)	[1.00]	−3.26	(13.42)	[0.66]
Large farms	0.50	(4.70)	[0.46]	−8.70	(0.49)	[1.00]	5.97	(5.27)	[0.13]
Forest activities	0.39	(0.99)	[0.34]	−2.87	(0.50)	[1.00]	0.34	(0.49)	[0.24]
Sub-total	−0.24	(3.12)	[0.55]	−9.03	(0.45)	[1.00]	4.11	(3.67)	[0.14]
South/South-East									
Small farms	−8.87	(4.27)	[0.99]	−4.09	(1.66)	[1.00]	−6.07	(4.11)	[0.93]
Large farms	−17.40	(4.18)	[1.00]	−4.75	(0.40)	[1.00]	−14.61	(4.26)	[1.00]
Forest activities	−1.17	(1.08)	[0.86]	−3.71	(0.56)	[1.00]	−0.67	(0.39)	[0.96]
Sub-total	−11.85	(1.06)	[1.00]	−4.33	(0.80)	[1.00]	−9.16	(0.99)	[1.00]
Brazil total	−7.20	(1.04)	[1.00]	−0.81	(0.40)	[0.99]	−6.62	(0.99)	[1.00]

Note: Results report the mean percentage change of income, the standard deviation (in parentheses), and the sample probability that producer income decreases [in brackets].

of large farms in the Center-West that, with reduced competition from the Amazon livestock sector, increase their income by an average of 6 per cent (although the large standard deviation suggests caution in using the mean, the probability indicates that large farm income has a considerable chance of increasing relative to the combined case).

The regions that gained from innovation outside the Amazon are the Center-West, and, perhaps surprisingly, the North-East. In the Center-West, the growth in agricultural income does not come as a surprise, given the large productivity improvements in annuals and livestock that have been reported in the region. In fact, the increase in income is limited by the improvements that occurred over the same period in the South/South-East region. In these two regions (Centre-West and South/South-East), the deteriorating terms of trade for both small and large farms, resulting from the substantial contemporaneous increase in the regions of productivity in annuals, limits the impact of income generation from the productivity improvements. Given that annuals products from different regions are highly substitutable, the market-clearing price decreases markedly as technological improvement occurs. In the South/South-East, the overall impact is to reduce small farm incomes by 6 per cent, and large farm incomes by 15 per cent.

The increase in income in the North-East by approximately 4 per cent is due to the innovation that occurred in perennials and livestock production, which do not compete with the innovating annuals in the other regions. Small farms appear to perform better, even though we assumed small and large farms in the North-East experienced similar rates of productivity improvements.[13] The uneven income distribution, which is a hallmark of the North-East, is reduced by the trend in productivity improvements that took place between 1985 and 1995.

Policy-related decomposition of sectoral and regional components of productivity improvements outside the Amazon

The focus for this section is to differentiate the impacts on deforestation and agricultural incomes of specific types of productivity improvements occurring in a region. The approach provides additional intuition on the mechanisms at work, and can be viewed as a counterfactual in case current productivity trends do not continue as predicted. Since this type of analysis has already been carried out elsewhere for innovation occurring inside the Amazon, we concentrate here on the specifics of innovation occurring outside the Amazon, but first summarize the results on innovation inside the Amazon. In a detailed analysis of its impact on deforestation, Cattaneo (2001 and 2002) concludes that livestock innovation in the Amazon is associated, in the long run, with the greatest increase in income for both small and large farms, but that this entails a substantial increase in the deforestation rate. Conversely, productivity improvements in perennials in the Amazon can reduce deforestation, but with lower income growth. It therefore appears that there is a tradeoff between income growth and a

[13] In the model, small farms and large farms compete for different pools of capital: large farms in the North-East appear not to be competitive relative to large farms innovating in other regions.

Table 9. *Impact on deforestation of different types of productivity improvements outside the Amazon: alternative scenarios*

	Mean change in deforestation (%)	*Standard deviation*	*Probability that deforestation will decrease*
TFP innovation			
Historical non-Amazon (HNA)	−26.64	(3.76)	[1.00]
HNA without North-East innovation	−21 .84	(4.61)	[1.00]
HNA without small farm innovation	−15.73	(2.29)	[1.00]
HNA without livestock innovation	21.54	(2.84)	[0.00]
Land-saving innovation			
Historical non-Amazon (HNA)	−34.92	(4.61)	[1.00]
HNA without North-East innovation	−30.16	(4.14)	[1.00]
HNA without small farm innovation	−27.05	(3.62)	[1.00]
HNA without livestock innovation	27.19	(3.25)	[0.00]

Note: Results report the mean percentage change of deforestation, the standard deviation (in parentheses), and the sample probability that deforestation decreases [in brackets].

reduction in deforestation, when considering productivity improvements in the Amazon.

The impact of productivity improvements occurring in the rest of Brazil, however, has not been analyzed in detail. We focus here on identifying those components of productivity improvements outside the Amazon that contribute to limiting deforestation and the income tradeoffs that may be involved. In particular, this section considers the role of productivity improvements in the North-East on small farms outside the Amazon and for specific commodities being produced. This is accomplished by removing the assumption that these innovations occurred from the historical trend scenario outside the Amazon and observing the outcome relative to the extra-Amazon historical trend scenario presented in the previous section. For example, to determine the impact of innovation in the North-East, we analyze a counterfactual of extra-Amazon innovation occurring only in the Center-West and South/South-East, and compare the results to those for non-Amazon historical trends reported in table 7 (for deforestation) and in table 8 (for income), which include the impact of innovation in the North-East.

What emerges quite clearly from the previous section – as seen in table 7 – is that overall technological change outside the Amazon by itself did not cause greater deforestation; in fact, it exerted a limiting influence on deforestation rates (with a probability of 1). In this context, it appears that innovation in the North-East and among small farms played a role in limiting deforestation. Assuming factor neutral innovation, if innovation in the North-East is eliminated from the simulation, deforestation in the Amazon decreases by 22 per cent instead of 27 per cent (table 9). The reason a lack of technological improvement in the North-East leads to a smaller decrease in the deforestation rate is that some capital is moved out of the North-East and into large farm livestock production in the Amazon. Small farm innovation outside the Amazon contributes to limit deforestation by avoiding relocation of small farms to the agricultural frontier; therefore, when small farm innovation is removed from the factor-neutral scenario, the decrease in deforestation rates is just 16 per cent instead of 27 per cent.

What clearly emerges from the results presented in table 9 is that innovation in livestock outside the Amazon is the real driving force in limiting deforestation. The production technology being innovated, whether livestock, annuals, or perennials, is a determining factor of the impact innovation has on deforestation. At first glance, it would appear from the results presented in table 7 that the general statement 'technological improvement in Brazilian agriculture caused movement to the agricultural frontier' is incorrect; however, the qualified statement that improvement in annuals – soy in particular – could lead to greater deforestation is correct (Kaimowitz and Smith, 1999). This can be inferred by the results obtained when improvements in livestock technologies outside the Amazon are removed. The deforestation results are reversed: technological improvement in annuals and perennials, if not complemented by innovation in livestock, causes major increases in deforestation rates.

Taking away livestock innovation from the historical scenario leads to an increase in deforestation that would likely be in the 20 per cent to 30 per cent range (depending on the type of innovation and factoring in uncertainty), as opposed to the considerable reduction for innovation outside the Amazon presented in the previous section. This highlights the finding that terms-of-trade effects favor production of livestock in the Amazon, when production in other regions shifts toward annuals and perennials as a result of technological improvement.

On the income side, the second column in table 10 shows that, if innovation in livestock had not been introduced, compared with the historical scenario, all regions except the Center-West would have been better off in terms of agricultural income, and the outcome would have been more equitable in the Center-West and South/South-East. If no livestock innovation had occurred in Brazil, the North-East, which had smaller but more diversified productivity gains than other regions, would have experienced a considerable increase in incomes for both small and large farms. The agricultural income growth in the North-East would be driven in this case by a shift of resources towards the production of perennials. The large differences in deforestation and income between the scenarios, with and without livestock innovation, indicate that policy makers are faced with trade-offs to the extent that the desirable environmental outcome associated with technological improvement in livestock outside the Amazon is attained at a cost in both agricultural income generation and income distribution objectives.

The type of development that occurred in the North-East, however, appears to have been beneficial for both the environment and agricultural income generation, as it would lead to less deforestation and higher incomes in Brazil as a whole, besides the obvious increase in income in the North-East. This can be seen in column 3 in table 10, which shows the change in value added that would have occurred if innovation in the North-East had not taken place – a 16 per cent decrease in North-East agricultural income and a 7.6 per cent decrease in Brazilian agricultural income relative to the 1995 observed values. From the results presented, one may state that

Table 10. *Impact on value added of total factor productivity improvements outside the Amazon*

	Historical non-Amazon (HNA)			*HNA without livestock innovation*			*HNA without North-East innovation*			*HNA without small farm innovation*		
Amazon												
Small farms	−17.83	(1.80)	[1.00]	−2.96	(0.89)	[1.00]	−17.53	(1.39)	[1.00]	−11.35	(1.86)	[1.00]
Large farms	−27.14	(2.06)	[1.00]	6.55	(1.91)	[0.00]	−25.33	(2.45)	[1.00]	−23.47	(1.64)	[1.00]
Forest activ.	−23.38	(2.30)	[1.00]	20.09	(2.95)	[0.00]	−20.32	(3.02)	[1.00]	−15.74	(1.69)	[1.00]
Total	−21.50	(1.83)	[1.00]	3.13	(1.25)	[0.00]	−20.35	(1.84)	[1.00]	−15.75	(1.55)	[1.00]
North-East												
Small farms	10.21	(6.84)	[0.06]	11.60	(4.25)	[0.00]	−14.12	(2.07)	[1.00]	−16.54	(1.34)	[1.00]
Large farms	−7.58	(6.30)	[0.88]	7.52	(5.93)	[0.12]	−22.19	(1.82)	[1.00]	16.60	(5.54)	[0.00]
Forest activ.	0.51	(0.39)	[0.10]	−2.24	(0.40)	[1.00]	4.14	(0.31)	[0.00]	1.17	(0.39)	[0.00]
Total	3.72	(3.64)	[0.16]	9.68	(2.47)	[0.00]	−16.21	(1.87)	[1.00]	−4.47	(1.53)	[1.00]
Center-West												
Small farms	−3.26	(13.42)	[0.66]	4.27	(1.05)	[0.00]	−8.98	(13.05)	[0.77]	−33.47	(2.56)	[1.00]
Large farms	5.97	(5.27)	[0.13]	1.06	(1.05)	[0.16]	5.58	(4.91)	[0.13]	22.95	(3.67)	[0.00]
Forest activ.	0.34	(0.49)	[0.24]	−2.10	(0.44)	[1.00]	−0.61	(0.64)	[0.83]	−0.03	(0.25)	[0.56]
Total	4.11	(3.67)	[0.14]	1.61	(0.94)	[0.05]	2.70	(3.14)	[0.20]	11.82	(2.86)	[0.00]
South/South-East												
Small farms	−6.07	(4.11)	[0.93]	−0.14	(2.37)	[0.52]	−1.19	(3.45)	[0.63]	−16.46	(1.96)	[1.00]
Large farms	−14.61	(4.26)	[1.00]	−3.47	(2.56)	[0.90]	−11.79	(4.06)	[1.00]	−1.14	(3.03)	[0.64]
Forest activ.	−0.67	(0.39)	[0.96]	−3.33	(0.48)	[1.00]	−1.50	(0.46)	[1.00]	−1.08	(0.23)	[1.00]
Total	−9.16	(0.99)	[1.00]	−1.58	(0.56)	[1.00]	−5.34	(0.66)	[1.00]	−9.81	(0.50)	[1.00]
Brazil total	−6.62	(0.99)	[1.00]	1.11	(0.77)	[0.08]	−7.63	(0.80)	[1.00]	−6.98	(0.50)	[1.00]

Note: Results report the mean percentage change of income, the standard deviation (in parentheses), and the sample probability that producer income decreases [in brackets].

innovation in the North-East could potentially be a win–win scenario, with the extent of the environmental improvement depending on the degree of innovation in livestock.

Small-farm productivity improvements outside the Amazon played an important role in achieving both income and equity objectives. The last column of table 10 illustrates what would have happened to agricultural income if large farms alone had innovated, leaving small farms behind: there would have been a predictable decrease in small-farm income, but also a decrease in national agricultural income, relative to the historical scenario. Here too, policy makers may have an appealing option to the extent that stimulating productivity improvements among small farms outside the Amazon would generate income, improve income distribution, and reduce deforestation.

To conclude this section, it is important to highlight the crucial role of livestock productivity improvements in determining the impacts on both incomes and deforestation. Technological improvements in the North-East and among small farms are potential win–win scenarios; however, the deforestation reductions are completely contingent on innovation in livestock production occurring outside the Amazon. At the same time, innovation in livestock has negative impacts on agricultural income. It therefore appears that this is an unavoidable tradeoff, albeit one that may be only partially under the policy makers' control.

Conclusions

This paper analyzes how productivity improvements in Brazilian agriculture, induced by the policy reforms of the 1980s and 1990s, may have affected deforestation rates in the Amazon and agricultural incomes in Brazil. What emerges is that, while productivity improvements inside the Amazon – particularly in livestock – tend to increase deforestation, the overall productivity improvements that occurred in Brazil as a whole during 1985–1995 are unlikely to have contributed substantially to increases in deforestation rates. This is the outcome of productivity improvements outside the Amazon, which limit deforestation and act as a countervailing force relative to productivity increases inside the Amazon. From an income generation perspective, the impact of overall historical productivity improvements in agriculture on aggregate national agricultural income has been negative. This is not uncommon with productivity improvements in agriculture, since demand for agricultural commodities often has a very elastic response.

The rates of technological innovation for livestock activities, both inside and outside the Amazon, play a major role in determining deforestation and agricultural income. Innovation in livestock in the Amazon contributes to increasing agricultural income in the region, but with greater deforestation rates, while innovation in livestock outside the Amazon leads to lower deforestation rates, but also lower agricultural incomes overall (both within and outside the Amazon). For example, innovation in annuals and perennials outside the Amazon, when not accompanied by innovation in livestock in those regions, unequivocally leads to an increase in deforestation rates. The results confirm the view that innovation in annuals outside the Amazon may have pushed some livestock producers to the agricultural frontier, but they also indicate that the livestock producers that did not migrate and did innovate to keep pace with rising land prices substantially limited this phenomenon and effectively contained deforestation rates.

A central result of the analysis is that the impact on deforestation of innovation in a specific agricultural sector depends strongly on whether it occurs inside or outside the Amazon. If an improvement in a sector in the Amazon increases deforestation, the same improvement outside the Amazon tends to decrease deforestation, and the opposite is also true. The underlying dynamic that drives changes in deforestation rates has to do with two factors: (i) how productivity changes affect the terms of trade for Amazon products and (ii) whether the Amazon sectors favored (or negatively affected) by the shift in relative prices make extensive use of land. When resources are pulled away from a sector outside the Amazon, the relative price of commodities produced by that same sector in the Amazon may increase, shifting local resources towards it. Using this line of reasoning, we observe that innovation in perennials, which have a lower land use per value of output, has exactly the opposite effect of innovation in livestock/pasture: innovation in perennials technology decreases deforestation if it occurs inside the Amazon, but increases it if it occurs outside the Amazon.

On the income side there is a similar symmetry, with livestock improvements being a good income generating option for producers in the Amazon (as reported in Cattaneo, 2002), due to limited labor availability in the region, but not so for producers outside the Amazon. Conversely, perennials, being more labor intensive, present limited returns in the Amazon, but are more attractive outside the Amazon. This is also due to the fact that, compared with livestock and annuals, perennials are more regionally differentiated products, with a lower price response in the national commodity market when supply increases.

The policy implications of these results can be subdivided into two themes. First, it appears that the productivity gains inside and outside the Amazon, driven by the policy reforms initiated in the 1980s, produced a precarious balance in deforestation rates at an average level of approximately 17,000 km^2/year (annual fluctuations notwithstanding). However, in the long run, since agricultural activities are competing for labor, capital, and land, the relative speed of innovation in different sectors and regions will matter and may break such-precarious equilibrium. If innovation in livestock activities outside the Amazon cannot maintain the pace of innovation in annuals (such as soy in the Center-West) a considerable increase in deforestation may occur in the near future. The second theme is of a more normative nature and has to do with the ability of policy makers to direct productivity improvements by dedicating resources to agricultural research, by deciding where to develop infrastructure, and through fiscal incentives, so as to accomplish both income and environmental objectives. In this respect, decomposing the impact of productivity improvements by region and farm size indicates that promoting innovation in the North-East and in small farm agriculture outside the Amazon could accomplish both goals; however, the overall outcome is likely to be contingent on the extent of innovation in livestock occurring inside and outside the Amazon.

Innovation in livestock engenders a trade-off: if it occurs in the Amazon, it improves incomes but increases deforestation, while, if it happens outside the Amazon, the reverse is true.

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Table AI. *Impact on value added of* land saving *improvements inside and outside the Amazon*

	All regions innovate			*Amazon only innovation*			*Innovation only outside of the Amazon*		
Amazon									
Small farms	2.26	(7.15)	[0.39]	45.98	(12.58)	[0.00]	−21.16	(1.66)	[1.00]
Large farms	−11.87	(7.98)	[0.91]	43.39	(15.37)	[0.00]	−33.68	(2.31)	[1.00]
Forest activities	−26.27	(3.81)	[1.00]	31.10	(5.62)	[0.00]	−26.35	(2.30)	[1.00]
Total	−6.02	(3.79)	[0.94]	43.17	(2.13)	[0.00]	−25.79	(1.84)	[1.00]
North-East									
Small farms	4.70	(5.29)	[0.21]	−2.16	(0.13)	[1.00]	6.85	(5.47)	[0.10]
Large farms	−9.88	(6.28)	[0.94]	−3.99	(0.31)	[1.00]	−6.06	(5.88)	[0.84]
Forest activ.	3.33	(0.63)	[0.00]	−1.16	(0.28)	[1.00]	1.42	(0.37)	[0.00]
Total	−0.37	(3.06)	[0.56]	−2.76	(0.18)	[1.00]	2.20	(3.23)	[0.26]
Center-West									
Small farms	15.43	(17.50)	[0.21]	−12.77	(0.40)	[1.00]	13.55	(18.03)	[0.26]
Large farms	8.35	(6.81)	[0.12]	−8.63	(0.55)	[1.00]	17.14	(7.73)	[0.01]
Forest activ.	3.51	(0.93)	[0.00]	−1.42	(0.45)	[1.00]	0.22	(0.56)	[0.32]
Total	9.59	(4.73)	[0.01]	−9.27	(0.44)	[1.00]	16.11	(5.48)	[0.00]
South/South-East									
Small farms	−10.04	(3.70)	[1.00]	−4.53	(1.27)	[1.00]	−7.30	(3.52)	[0.99]
Large farms	−19.41	(4.14)	[1.00]	−4.46	(0.77)	[1.00]	−16.90	(4.22)	[1.00]
Forest activ.	5.35	(0.90)	[0.00]	−1.41	(0.52)	[1.00]	1.46	(0.33)	[0.00]
Total	−13.01	(0.97)	[1.00]	−4.36	(0.42)	[1.00]	−10.65	(0.98)	[1.00]
Brazil total	−7.64	(1.02)	[1.00]	−0.24	(0.12)	[0.96]	−6.83	(1.03)	[1.00]

Note: Results report the mean percentage change of income, the standard deviation (in parentheses), and the sample probability that producer income decreases [in brackets].

Table A2. *Impact on value added of* land saving *improvements outside the Amazon*

	Historical non-Amazon (HNA)			*HNA without livestock innovation*			*HNA without North-East innovation*			*HNA without small farm innovation*		
Amazon												
Small farms	−21.16	(1.66)	[1.00]	−1.54	(1.01)	[0.95]	−19.33	(1.46)	[1.00]	−17.98	(1.02)	[1.00]
Large farms	−33.68	(2.31)	[1.00]	7.94	(2.09)	[0.00]	−31.18	(2.34)	[1.00]	−30.41	(1.99)	[1.00]
Forest activ.	−26.35	(2.30)	[1.00]	27.42	(3.56)	[0.00]	−24.06	(2.25)	[1.00]	−21.89	(2.00)	[1.00]
Total	−25.79	(1.84)	[1.00]	5.33	(1.46)	[0.00]	−23.69	(1.75)	[1.00]	−22.41	(1.42)	[1.00]
North-East												
Small farms	6.85	(5.47)	[0.10]	12.10	(4.09)	[0.00]	−16.50	(2.02)	[1.00]	−16.92	(0.92)	[1.00]
Large farms	−6.06	(5.88)	[0.84]	10.82	(6.21)	[0.04]	−24.53	(2.24)	[1.00]	12.38	(5.23)	[0.00]
Forest activ.	1.42	(0.37)	[0.00]	−2.31	(0.43)	[1.00]	5.76	(0.33)	[0.00]	2.42	(0.48)	[0.00]
Total	2.20	(3.23)	[0.26]	11.12	(2.56)	[0.00]	−18.43	(2.00)	[1.00]	−6.11	(1.60)	[1.00]
Center-West												
Small farms	13.55	(18.03)	[0.26]	9.99	(1.51)	[0.00]	7.98	(16.70)	[0.39]	−16.73	(1.56)	[1.00]
Large farms	17.14	(7.73)	[0.01]	4.18	(1.13)	[0.00]	19.59	(7.86)	[0.00]	36.07	(6.68)	[0.00]
Forest activ.	0.22	(0.56)	[0.32]	−2.18	(0.54)	[1.00]	−1.00	(0.57)	[0.99]	0.08	(0.15)	[0.31]
Total	16.11	(5.48)	[0.00]	5.15	(1.12)	[0.00]	16.97	(5.65)	[0.00]	25.36	(5.22)	[0.00]
South/South-East												
Small farms	−7.30	(3.52)	[0.99]	0.94	(2.10)	[0.34]	−2.57	(3.19)	[0.78]	−15.59	(1.58)	[1.00]
Large farms	−16.90	(4.22)	[1.00]	−2.74	(2.37)	[0.86]	−13.90	(4.42)	[1.00]	−8.10	(3.36)	[0.99]
Forest activ.	1.46	(0.33)	[0.00]	−2.87	(0.51)	[1.00]	0.35	(0.30)	[0.13]	0.98	(0.24)	[0.00]
Total	−10.65	(0.98)	[1.00]	−0.67	(0.49)	[0.91]	−6.86	(0.87)	[1.00]	−11.94	(0.85)	[1.00]
Brazil total	−6.83	(1.03)	[1.00]	2.54	(0.78)	[0.00]	−7.62	(0.84)	[1.00]	−7.65	(0.56)	[1.00]

Note: Results report the mean percentage change of income, the standard deviation (in parentheses), and the sample probability that producer income decreases [in brackets].