

**Agricultural Intensification by Smallholders
in the Western Brazilian Amazon**
From Deforestation to Sustainable Land Use

Stephen A. Vosti,
Julie Witcover, and
Chantal Line Carpentier

**RESEARCH
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Foreword

In countries with a vast expanse of sparsely populated land, a greater burden inevitably falls on marginal lands to house and employ growing populations and to contribute to national income growth. Frontier areas opened up for strategic or economic reasons often become home to farmers, although conditions are often ill suited to agriculture. The prospect of a cycle of poverty and environmental degradation makes these areas a focal point for those concerned with feeding the world's poorest while protecting the natural resource base.

Developing-economy policymakers must consider how to balance environmental sustainability with development objectives of economic growth and poverty alleviation in frontier regions. They must decide when, where, and how to tap these areas for productive use, or whether they should be tapped at all given the agronomic difficulties there. Should they actively protect local watershed resources and global environmental services (such as carbon sequestration and biodiversity)? They must do so in a world that so far lacks global institutions to compensate forest users for the revenue they forgo when they leave the forest untouched.

This report provides input to those decisions in the form of empirical information about trade-offs and complementarities among development goals. It does so with a focus on tropical moist forests in agricultural frontier areas, using data from in-depth fieldwork in study sites in the western Brazilian Amazon. There, as elsewhere, tropical moist forests continue to fall, with clearing driven in part by demand for agricultural land.

National strategies differ widely in the type and degree of their reliance on forest margins to contribute to economic growth, via ecotourism or new ground for production of commodities such as cattle, soybeans, and coffee, not to mention raw natural resources, including timber, or other national goals, such as protected park lands, areas reserved for indigenous groups, or settlement areas for the landless poor.

In each locale, the prevalence of often impoverished smallholders over larger commercial interests varies, and with it their relative roles in deforestation. To better understand land use relationships, this IFPRI research report centers on smallholder settlements. It does so in areas changing, as are so many marginal lands, in response to more integrated market links with national and regional economies.

This report is published in conjunction with another IFPRI report looking at how the broader Brazilian economy affects deforestation and vice versa (*Balancing Agricultural Development and Deforestation in the Brazilian Amazon*, by Andrea Cattaneo) as well as other tropical forest margins studies ongoing under the Alternatives-to Slash-and-Burn Agriculture Programme (ASB), a research initiative coordinated by the World Agroforestry Center (ICRAF).

The in-depth fieldwork presented in this report has identified economic and biophysical factors leading small-scale farmers in two settlement projects in the western Brazilian Ama-

zon to convert forest to agriculture. Results indicate a trade-off between poverty and the environment. By and large, smallholders in the study were neither well off nor extremely poor. The research finds that although smallholders are exhausting private forests, their incomes are rising. The results are in keeping with regional statistics for Brazil that find human development indicators for the Amazon moving close to those for the country as a whole by 1996. The report finds some evidence that where farmers remain isolated, lower incomes are likely to persist. It remains a research question (that the methodology used here could help answer if applied elsewhere) whether such conditions could spark a vicious cycle wherein poverty causes and is deepened by environmental degradation.

The report examines the potential for policy and technological change to slow deforestation rates in the study area, by comparing the effects of these changes on income. Traditional regulatory policies have substantial negative income consequences for smallholders. At the same time, efforts to intensify agriculture are apt to speed deforestation. Labor-using intensification strategies on cleared land only slightly retard the pace of deforestation. More successful in boosting incomes and slowing deforestation is intensive but sustainable use of forests, which would require careful and potentially expensive monitoring, not to mention considerable training of personnel.

These findings can be used by policymakers who must balance instruments that regulate forest and land use—relying on administrative structures for monitoring and enforcement plus appropriate penalty-setting—with those that require a less overt public sector role by altering incentives to induce farmers to conserve forest. They must do so in areas often remote from policymaking centers and with weak institutional structures linked to those centers, where policy implementation and effects may diverge from original policy objectives.

This research points to the need for creative use of policy cognizant of private incentives in areas undergoing economic development and an expanding frontier, and explicit examination of trade-offs in marginal areas with less dynamic links to broader markets. Researchers and policymakers concerned with agricultural frontiers and beyond can use quantitative measures of the trade-offs among policy objectives such as those found here, and the research methods used to generate them, to make environmental objectives more compatible with those of growth and poverty alleviation.

Joachim von Braun
Director General, IFPRI

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Dedication

Julie Witcover dedicates her contribution to this report and the fieldwork and analysis behind it to Bruce Stone. His support, encouragement, and companionship throughout made it possible.

Summary

In the Amazon and elsewhere, international concerns about the environment sometimes clash with national and local concerns about development via agricultural growth. While roughly 7,600 square kilometers of Amazonian rain forest were cut and burned between 1995 and 1997, agricultural income grew and child mortality and malnutrition improved. From a global standpoint, however, retaining the forest is important because it sequesters carbon and is home to many species not found elsewhere.

Incentives for land users to protect the forest are piecemeal in nature and uncertain in outcome. Hence, protection of the forest generally falls to the public sector. Policies can (1) directly regulate land use, incorporating penalties for violations in order to shift incentives away from deforestation; (2) improve relative economic benefits of activities that discourage deforestation; or (3) combine both approaches. On frontiers where land is abundant and labor scarce—including the project areas in this report—direct regulatory approaches are physically difficult to enforce and fiscally expensive.

This report presents trade-offs among a “critical triangle” of development objectives—environmental sustainability, economic growth, and poverty alleviation—associated with different uses of the forest in two settlement projects in the western Brazilian Amazon. It finds that settlers continue to deforest, primarily for pasture, despite strengthening of legal prohibitions, improved market links to the broader economy, and rising regional incomes and welfare. A supplement to approaches that look at deforestation from a macroeconomic viewpoint, this report focuses on smallholders’ decisionmaking—important because Brazilian migration policies designed to alleviate poverty have made this group a pivotal force in both deforestation and economic growth in the Amazon.

Drawing on field data collected from farm households surveyed in 1994 and 1996, the report uses descriptive analysis to quantify current land use patterns. It then explores land use determinants using multivariate regression analysis and simulates a representative household’s responses to particular policy and technology changes, or both, using a linear programming model that explicitly incorporates biophysical constraints on production.

The report finds that the relative profitability of alternative crop, livestock, and extractive activities, conditioned by labor scarcity, favors livestock production systems over other activities. Returns per labor unit to even low-technology livestock systems exceed by a ratio of 7 to 1 those generated by forest extractive activities (gathering Brazil nuts, for example). With such a large difference in profits, it seems clear that small farms will not retain natural forest in the long run.

Even new technologies or relative price shifts that alter labor needs may not induce large changes in land use patterns, since seasonal labor bottlenecks preclude broad expansion of labor-intensive agroforestry or perennial production systems, and risks are higher. Switching

from pasture to other land uses can be agronomically difficult, costly, and slow, all of which favor the expansion of pasture.

Despite constraints, smallholders' agricultural activities have by and large helped them escape poverty and increase their assets. Demand for agricultural land is found to be the primary force behind deforestation—*not* demand for soil nutrients, although nutrient depletion affects land use management strategies and, ultimately, incomes. But while many smallholders succeed, others fail. Liquidity plays a critical role during the initial settlement phase: insufficient resources account for much of the owner turnover in newly settled areas.

Many policy actions will reduce deforestation at the expense of household income, or vice versa. For policymakers to change smallholder deforestation patterns *and* improve livelihoods, however, is difficult and expensive. Although several promising mechanisms for slowing deforestation and increasing household income emerge from this research, most face considerable obstacles to implementation.

Mandating that some proportion of private lands must remain in forest has largely failed because the cost of enforcement is prohibitive. For restrictions to be effective, they must reduce the incomes of smallholders. If profits remain high, farmers will ignore the restrictions.

Zoning to keep farmers away from land with poor soils is an important tool in guiding the use of forested and cleared lands. Research shows, however, that incomes generated by even low-quality soils are sufficient to sustain the average household; encroachment into protected areas with nutrient-poor soils should therefore be expected. Steep topography and severe waterlogging (*not* soil fertility constraints) were the biophysical conditions that significantly slowed the pace of deforestation.

Speeding up formal processes of securing land tenure would increase the proportion of land in pasture and perennials but not conserve forest. New arrivals to established projects deforest simply in order to farm.

Reducing transport time to local markets through, for example, investments in road systems also increases deforestation by lowering the cost of participating in markets. The volume and type of traffic on rural roads seems to have a greater impact on land use than road surfaces per se, and greater traffic favors perennial systems over pasture.

By incorporating legumes into pastures, the useful life of soils can be extended and carbon emissions reduced. Deforestation could increase, however, because farmers would have more income with which to hire labor to expand pasture area.

An experimental system of sustainably extracting small quantities of timber from private forest reserves could substantially raise incomes and slow deforestation by adding value to remaining forests. The government has not encouraged its use, however, because the cost of ensuring that landowners are using sustainable extraction techniques would be high. Extraction of nontimber forest products has not been a forest-saving moneymaker because product availability is limited and often seasonal, and product values are low. Finally, emerging markets for carbon might slow deforestation by adding value to standing forests for the carbon they retain, but this policy option has not been tried in the study areas. The size of the income generated would have to be large to persuade farmers not to deforest, since agriculture is so profitable. Carbon payments would also have to cover implementation and transaction costs, including monitoring and enforcement expenses.

Much research remains to be done. New technology is needed to restore degraded pasture. Financial analysis on agroforestry systems that combine fast-growing timber species with perennials or other crops would be useful. Such systems could reduce deforestation if obstacles such as high labor requirements, undeveloped markets, and high up-front investment could be overcome.

Ways must be found to tap some of the benefits generated by agricultural intensification to help finance rigorous enforcement of deforestation regulations. Empirical research on mechanisms to lower administrative, monitoring, and enforcement costs of policy implementation is sorely needed.

This research confirms that large, swift population movements into forest margin areas trigger increased deforestation. Still, the finding that smallholders in the project areas have largely succeeded in climbing out of poverty by using previously forested land refutes the idea that deforestation in the Amazon and elsewhere is necessarily part of a vicious cycle in which poverty begets degradation and itself deepens after degradation occurs. Results hinge on the underlying profitability of expanding agriculture, even with substantial constraints on small farmers—poor soils, limited access to credit, and low availability of hired labor.

CHAPTER 1

Introduction

Between 1960 and 1990, the world lost an estimated 20 percent of its tropical forests (Bryant, Nielsen, and Tangley 1997). Margins of tropical moist forests have come under direct pressure largely from small-scale, semi-subsistence agriculture in Sub-Saharan Africa and Asia and settlement and infrastructure projects with a considerable small-scale agricultural component in Latin America and Asia (FAO 1997). The agricultural activity has brought economic benefits and can help alleviate poverty, but agronomic limitations of forest margin soils and climate have led some to question the size and sustainability of production gains. Continued deforestation also threatens global environmental services such as sequestering carbon and providing biodiversity, with annual burning from intentional or runaway fires causing local damage in the form of destroyed property, respiratory ailments, and transportation disruptions (Chomitz and Thomas 2000; Nepstad et al. 1999). The trends have sparked considerable debate about agriculture's proper role, if any, in forest margins.

The debate centers on how to manage forest margins so as to meet simultaneously a “critical triangle” of three development objectives: economic growth via agriculture, environmental sustainability, and poverty alleviation (Vosti and Reardon 1997). Increasingly, attention is turning to the world's largest remaining contiguous forests, such as the Amazon rainforest and the Congo Basin in Africa, because of the global environmental services they provide, which can be lost if forest areas are fragmented (Bryant, Nielsen, and Tangley 1997). Where current incentives favor deforestation for logging or agriculture, the question being debated is whether walling off forests from use is feasible or desirable from a policy standpoint (Bowles et al. 1998; Chazdon 1998; and a debate by Gascon et al. 1998 via an exchange of letters in *Science*), especially given national strategies that look to frontier areas as potential engines for future growth (see, for example, Brazil 1997).

Behind these efforts is a need to understand more precisely the nature and magnitude of apparent economic and environmental trade-offs, and whether these trade-offs are inevitable (see Turner et al. 1995 for a general overview of these issues, especially Chapter 7; Bunker 1985; Dourojeanni 1990; and IDB 1992, especially Chapter 4, for a focus on the Amazon; McGaughey and Gregersen 1982 for more on forest-based activities in Latin America; and for agriculture in the Brazilian Amazon, see Homma 1998 and Serrão, Nepstad, and Walker 1996). On all sides of the debate are those searching for solutions that can preserve rainforest while meeting the livelihood needs of forest margin inhabitants and growth requirements of regional or national policymakers—a balance sometimes termed sustainable intensification.

Striking this balance involves changing farmers' incentives to expand agriculture in relatively abundant land areas and understanding the processes currently driving deforestation for agriculture. The remainder of this section outlines existing research on the problem and describes and justifies the focus of this report within that context.

Economic models of these processes generally have one or more of several conceptions of what will limit agriculture's encroachment into forest,¹ with much work emphasizing the role of one of two forces behind agricultural expansion. Agricultural profitability generates impetus for clearing forests within a certain range of markets and under certain economic conditions (a spatial approach used in, for example, Chomitz and Gray 1996, and, for timber, Stone 1998). Beyond that range or even within it, agronomic unsuitability of land could provide its own impetus, especially for those most at risk for poverty who must rely on forests rather than purchased inputs for nutrients (Chomitz and Thomas 2000; Vosti and Witcover 1996b; Vosti and Reardon 1992).² New technologies, however, can relieve agronomic constraints beyond the short term (on soybeans, Fearnside 2001 and Kaimowitz and Smith 2001; on improved pastures, Yanggen and Reardon 2001).

According to some, limited demand at either a global or local scale sets the relevant radius from markets within which agricultural production is viable (the Borlaug hypothesis at the global scale and "full-belly" or subsistence hypotheses at local scales) (see Angelsen and Kaimowitz 2001c for a brief review of this literature). This implies that at a certain point land left in forest ceases to have enough value as agricultural land to justify conversion. For others, income growth will play a central role in contracting the radius from markets for

economic activity as it brings higher local valuation of the environment, limiting deforestation (see, for example, Barbier 2001 for a summary of the Environmental Kuznets Curve economic model underlying this approach and empirical papers applying it). Another way income growth can draw pressure off forest is by generating greater opportunities in nonagriculture and nonforest sectors (Rudel 2001). Higher valuation of the forests can also come via extractive products, so some limited economic activity extending into the forest may be justified, although it could potentially do some environmental damage (see, for example, McGaughey and Gregersen 1982; Panayotou and Ashton 1992; Peters 1997).³ In others' view, scarcity (or outright exhaustion) of additional land for expansion is the primary condition that will change incentives in a way that limits agricultural expansion (see, for example, White et al. 2001). Until then agriculture should expand in response to improved profitability, given prices and under conditions prevalent in forest margins, where land is relatively abundant and cheap.⁴ Even here, though, local or national institutional and market contexts; how a new technology uses land, labor, and capital; and the time frame under study may lead to an opposite result (Angelsen et al. 2001; Barbier 2001; Deacon 1994).

Deforestation models also reflect the multiscale nature of the phenomenon. Some focus on macroeconomic forces—capital and migratory flows as well as price

¹They are not necessarily mutually exclusive; there are conditions under which each could be consistent with standard economic theory. As models for empirical studies, they reflect different priors about prevalent conditions in developing-country forest margins.

²Costs from regulatory penalties or forest clearing technology could have similar effects.

³The inclusion of forest-based activities in models of deforestation for agriculture (drawing on existing forestry work) is still in its infancy, perhaps reflecting a disciplinary divide.

⁴Higher profits could come from higher-yielding technologies, but some believe farmers will not adopt land-intensifying technologies as long as land is abundant (Boserup 1981).

signals moving to and from forest margins under particular policy regimes—that help determine the boundaries of an economy’s extensive margin (see, for example, Southgate, Sanders, and Ehui 1990; Southgate, Sierra, and Brown 1991; Rudel and Roper 1997). Others concentrate at the regional level on factors such as population or infrastructure density, income levels, local market conditions, land uses, and agronomic potential (but pay less attention to the links among them) for their role in shaping local land use patterns (Chomitz and Gray 1996; Dale et al. 1993; Pfaff 1997). Still others examine one type of heterogeneous land user—usually the household farm rather than the large-scale firm—who makes deforestation decisions as part of livelihood strategies based on available resources given local conditions (Pichón 1997; Walker, Moran, and Anselin 2000; Walker and Smith 1993 for timber companies). Attention is also paid to a role for institutions—particularly property rights regimes—in deforestation patterns (Deacon 1994, 1995, 1999; Alston, Libecap, and Schneider 1995; see also papers in Barbier and Burgess 2001).

In a comprehensive review of 146 economic models of deforestation spanning these theoretical constructs and scales, Kaimowitz and Angelsen (1998) note some commonality in findings: ease of access to forest and to long-distance trade paths increases deforestation rates and so do higher agricultural and timber prices or lower rural wages. Differences in study design, data quality and availability, and limited focus of individual studies regarding study site, time period, and analytical tools used hampered definitive cross-context tests of specific hypotheses and thus policy prescriptions.

Studies at the national level, usually reduced-form regressions, are plagued by poor data quality (especially as regards forest cover). Aggregate data or interpolation methods used to fill in for missing data sometimes mask heterogeneity, or generate it, in socioeconomic and biophysical measures. Such methods rule out cross-country analyses that focus on forest cover as a dependent variable and use population as an explanatory variable (see a description in Barbier 2001). Regional studies suffer from some of these difficulties and vary considerably in theoretical structure (for instance, some include population or infrastructure density as endogenous, some not), so different hypotheses are tested.⁵ Household studies are too few to discern broader patterns, in part because data at this level remain difficult and expensive to collect, while secondary data have become more readily available. At the household level, though, models have a strong (and more similar) theoretical footing, in part because the decisionmaking unit jibes with the unit of analysis, making microeconomic theory more directly applicable. This, plus the data shortage, has led to more analytical than empirical models at this level.

Problems at each scale of analysis contribute to what Kaimowitz and Angelsen (1998) highlight in their review as inconclusive or ambiguous findings about the effects of macroeconomic forces, population and migration, changes in productivity and input markets (including land markets and tenure security), and household wealth—or poverty—on deforestation. Later, Barbier and Burgess (2001) include papers on deforestation that emphasize economic modeling techniques that incorporate spatial features and institutional factors (including

⁵The theoretical differences are not so surprising given that that review found no analytical models—perhaps requiring models with heterogeneous users (via game theory)—at this level. Since then, there have been some game theoretic approaches to forest margins land use, particularly on conflict over land tenure (Angelsen 2001, for example) and their empirical application (Alston, Libecap, and Mueller 1999).

placement of parks and reserves). Barbier (2001) nests, in a cross-country analysis, hypotheses about deforestation effects of income, structure of the agricultural sector, and institutional factors (using some recently available data on corruption and political stability, usually singly tested in previous papers). He finds strong links between structure of the agricultural sector and agricultural expansion (the latter proxying for loss of forest cover given data problems), indications that population and measures of political corruption and stability are important regionally, and regionally spotty evidence for an Environmental Kuznets Curve (but always implying an average income turning point toward forest preservation at levels considerably higher than current averages). Cropper, Puri, and Griffiths (2001) find preserved areas more likely to be located in areas less suitable for agriculture (in Thailand) and Nelson, Harris, and Stone (2001) find evidence (for Panama) that deforestation will continue in designated protected areas if other economic conditions are favorable. At household level, Barrett (1999) makes a theoretical case that food price risk could promote deforestation in food-buying households.

Considerable effort since the Kaimowitz and Angelsen review has also centered on deforestation effects of agricultural intensification (see studies assembled in Angelsen and Kaimowitz 2001b and Lee and Barrett 2001; Cattaneo 2001a,b, 2002). This is perhaps because, if agricultural intensification takes pressure off forests, it offers a policy entry point to promote a “win-win-win” scenario on critical triangle goals of environmental sustainability, economic growth, and poverty alleviation. Where these studies take technology adoption seriously, moreover, they touch on other research gaps, specifically how household poverty, input markets, and at least some demographic aspects (either directly or indirectly through examination of labor markets) affect the deforestation process (for example, Gockowski, Nkamleu, and Wendt

2001; Tomich et al. 2001; Vosti et al. 2001a).

Mixed results persist in these studies, causing early optimism to fade about the potential for new technologies to take pressure off forests (Angelsen and Kaimowitz 2001c,d; Lee, Ferraro, and Barrett 2001). The results also call into question assumptions underlying that optimism—namely that meeting subsistence or some other fixed set of requirements provides a primary rationale for continued deforestation. Attempts to link emerging empirical results with theory based on particular economic conditions (factor endowments, institutional contexts, and macroeconomic environment) and technological characteristics (relative and absolute use of land, labor, and capital—and their substitutability—given farmers’ access in limited input markets) have begun (Angelsen et al. 2001; Angelsen and Kaimowitz 2001d). They have borne fruit in the form of recommendations, carefully conditioned by economic conditions and technology specifics. These highlight the importance of the extent to which the area or individual land user under study is linked to outside markets for inputs (especially for land, labor, and capital) and outputs, as well as of the elasticity of demand for those outputs. The new studies have swept away earlier years’ conventional wisdom of the small-scale farmer driven to deforest for subsistence in the face of severe agronomic constraints and near complete market isolation as a stylized special case. Instead, they favor a view that market links are strengthening in most forest margins. They have yet to lead, however, to sweeping conclusions about where and how economic growth will remove pressure from the forests (see policy recommendations with caveats in Angelsen and Kaimowitz 2001a,d, Kaimowitz and Angelsen 2001, and Lee et al. 2001).

This report focuses on deforestation and land use patterns among small-scale agriculturalists in two settlement projects in two states of the western Brazilian Amazon; it

emphasizes decisionmaking by farmers and explores its consequences for economic growth, poverty alleviation, and environmental sustainability, as well as the potential for policy to mitigate trade-off.⁶ It allows for broader hypothesis testing than some earlier studies by focusing on more than one site, for more than one year, using more than one analytical tool (see the Methods section below).

Setting and research focus were selected with research gaps and policy relevance in mind. The Amazon rainforest has broad importance as one of the last remaining frontier forests that is vast and intact enough to provide important environmental services (Bryant, Nielsen, and Tangle 1997). The fate of its carbon stocks, ranging between 140 and 350 tons per hectare, and biodiversity—likely over half the world's species (Lele et al. 2000)—are under discussion as the world moves toward a revisit of the Rio conference and negotiations on the Kyoto Protocol. Policy analysis in Brazil, particularly with methods that can speak to consequences of proposed policies, has much to contribute at this time. Sixty percent of the Amazon's 5.5 million square kilometers fall within Brazilian borders;⁷ lively discussion is ongoing there about development strategies for the region (J. Valentim, personal communication 2000). Current government plans include (and past policies have in-

cluded) deforestation and forest use regulations; zoning efforts; land set-asides for parks, reserves, and indigenous groups; credit programs; government-sponsored migration; infrastructure decisions; and advances in agricultural and extractive technologies for the humid tropics (Brazil 1997; Acre 2000; Homma 1998; Lele et al. 2000; Serrão and Homma 1993; Serrão et al. 1996; Valentim and Vosti forthcoming).

Within the Brazilian Amazon, the western states of Acre and Rondônia—the focus of this study—provide an opportunity to examine agriculture's role in the frontier development process as it unfolds. Compared with the eastern Amazon, this is a less established frontier, more recently connected to the rest of Brazil and settled by agriculturalists. With the exception of one area of relatively high fertility soils (Ouro Preto do Oeste, Rondônia), the western Amazon is also the focus of fewer studies with an economic perspective.⁸ The states themselves provide distinct examples of different settlement histories, including historical forest use, magnitude of migration, agricultural policies, and degree and timing of links to the broader Brazilian economy. This part of the western Amazon may also be on the brink of large economic changes as port and road facilities recently finished or nearing completion link this area to international trade (for flows of goods and people). Research tools that can shed light on likely

⁶Biophysical research done in conjunction with this research assessed certain global environmental services in forest margins, notably carbon stocks and biodiversity (phase II reports of the Alternatives to Slash-and-Burn Agriculture Programme). This report uses deforestation to proxy for their loss and focuses on production-related environmental problems, particularly soil degradation.

⁷The rainforest areas are covered by what is called the Legal Amazon; this plus other land within the same states comprises Brazil's Northern region (see, for example, Chomitz and Thomas 2000), used in compiling regional statistics. Unless otherwise noted, all secondary data in this report for the Brazilian Amazon refers to the North, not the Legal Amazon.

⁸An overview of the literature for the eastern Brazilian Amazon, focusing on the state of Pará, and for the western Brazilian Amazon, focusing on Ouro Preto do Oeste in the state of Rondônia, plus studies emerging from the research sites under examination here, is presented in the next section of this chapter on research on deforestation and agriculture in the Brazilian Amazon.

responses of current inhabitants to proposed policies and imminent economic changes in this area are timely.

Focusing on small-scale agriculture allows direct study of the link between poverty and environment, particularly the land use and investment decisions (including deforestation) of farmers under considerable production constraints—some of them agronomic. The research provides data points and replicable methodologies available for cross-site and cross-country comparisons to illuminate more broadly the role of small-scale agriculture in frontier development. In tropical forest margins worldwide, small-scale agriculture often gains a foothold in the wake of extractive activities or in response to government incentives (Southgate 1990; Sunderlin 1996),⁹ and it is one of the several types of user groups found. A more comprehensive understanding of the frontier expansion process and of the role of small-scale agriculture within it awaits development of multiactor regional models, to which research on small-scale agriculture (along with research focusing on other land users) is a necessary precursor.¹⁰ Documenting agricultural productivity and poverty among smallholders is particularly relevant in Brazil because this group is an important presence in the Amazon demographically and economically. Schmink and Wood (1984) document two settlement projects that are part of a larger effort to alleviate poverty while promoting agricultural growth. Some 750,000 farmers have holdings of less than 100 hectares in Brazil's Legal Amazon and contribute some 36 percent of agricultural GDP from the Northern region, according to the most recent agricultural census (IBGE 1998).

Taking a household perspective can help unveil how factors originating at multiple scales—macroeconomic, regional, or within the household or on the farm—play out in specific land use decisions. This level of analysis is critical to capture the interplay between biophysical and economic factors in deforestation decisions precisely because it sidesteps many aggregation issues that complicate interpretation of higher scale models. It is a building block for understanding deforestation patterns at higher geographic scales, since local conditions emerge in part from land users' aggregate behavior. It provides an especially important complement to regional and national economic models that often assume seamless market connections, given that tropical forest margins are remote and in developing countries. The household-level perspective allows analysis to capture more concretely—in ways conforming to local conditions shaped by local institutions—the consequences for farmers of imperfectly functioning markets or inadequate access to markets. The specificity of conditions translates into more reliable figures in terms of magnitude of farmers' response to a given policy, which can aid in analysis of policies already in place or a search for new policy tools.

Research setting, scale, and methods were also chosen with the idea of reaping the potential benefits of cross-country and cross-scale work (Vosti, Witcover, and Carpentier 1998). Selection was done in conjunction with micro-level research ongoing in other forest margins via the Alternatives to Slash-and-Burn Agriculture Programme (ASB) (Avila 1994). This work has since included assessments of socioeconomic and

⁹Small-scale agriculture has followed logging in Southeast Asia, oil exploration in Ecuador and Central Africa, and been the focus of settlement projects in Brazil and Indonesia.

¹⁰In Brazil, attempts to allocate deforestation across land users is as difficult as it is elsewhere (Sunderlin 1996). Walker, Moran, and Anselin (2000) report that estimates in the literature of smallholders responsibility for deforestation range from 30 to 75 percent of overall Brazilian deforestation; Alston, Libecap, and Mueller (1999) describe how different agencies within Brazil disagree about current trends.

biophysical consequences of technologies (shedding light on farmers' ability to adopt them) using similar research methods (Gockowski, Nkamleu, and Wendt 2001; Tomich et al. 1998; Tomich et al. 2001; Vosti et al. 2001). Research at the regional level on institutional structures (Sydenstricker 1998) led to identification of additional factors (for example, local organizations and marketing structures) important for the household perspective. At the macroeconomic level, a regionally disaggregated computable general equilibrium (CGE) model for Brazil was developed in order to measure effects on Amazonian deforestation (and migration there) of broader economic and technological shifts in Brazil, and of Amazonian deforestation on the broader national economy (Cattaneo 2001a, b, 2002.)

The next section provides a brief overview of economic trends associated with deforestation in the study area. Valentim and Vosti (forthcoming) summarize the process in Acre and Rondônia in greater detail, drawing on much of a considerable literature that exists for the entire Brazilian Amazon (for example, Bunker 1985; Gheerbrant 1988; Homma 1998; Lele et al. 2000; Ozorio de Almeida and Campari 1995). For a general overview of broader trends throughout Brazil, see Fausto 1999.

Economic Development and Deforestation in the Western Brazilian Amazon

Presumably since before European colonization, small indigenous groups practiced extraction and a rotating system of slash-and-burn agriculture in the Amazon. While pockets of agriculture moved into floodplains of the Amazon basin and upland regions in the eastern Amazon starting in the 19th century, the search for rubber brought an influx of economic activity to the western Amazon. Brazilians, particularly from the poor northeastern region moved west with the promise of jobs; Acre, which was

part of Bolivia until early in the 20th century, was one of the destinations. They found there a reality of virtual indentured servitude. Forests were disturbed by paths linking rubber trees (with some clearing for agriculture to feed workers), but remained largely intact. The bust to this economic cycle came with the advent of plantation rubber in Southeast Asia, which had better access to trade routes (for more on the rubber boom, see Gheerbrant 1988, Chapter 4).

Renewed economic interest in the region did not come until the 1960s, when the government of Brazil initiated "Operation Amazon." The government created agencies devoted to regional development, often via subsidized credit to ranching and mining interests, and it began construction on an ambitious road network to link the Amazon region to the rest of the country. With the first paved road linking the western state of Rondônia to the south in the late 1960s came the beginnings of colonization (Jones et al. 1995). The intention behind government programs was to resolve national security issues associated with low population densities in the region, while sparking economic activity that would help fuel striking growth rates being achieved in Brazil. From these agencies' inception until the mid-1990s, nearly 400 credit projects were approved for the Amazon, just under 10 percent of them in Acre and Rondônia.

Tough economic times following the oil crisis in the 1970s sparked an additional development initiative in Brazil: the opening of sizable tracts of land to small-scale farming at token prices in the Amazon, in order to relieve the increasing poverty and landlessness plaguing Brazil's economic centers in the south and southeast (Wood and Wilson 1984). Busloads of migrants, displaced by infrastructure projects and structural change in agriculture, flooded into the region on and along government-built roads or into government-sponsored settlement projects on plots of up to 100 hectares, blocked out with little regard to agronomic suitability or water access. They began

agriculture with practices imported from vastly different agronomic and climatic conditions and few tools to fight pests that plagued crops and animals. Rampant malaria added to early settlers' difficulties (de Bartolomé and Vosti 1995). The government set up health posts as well as schools in the settlement projects, but trained personnel were difficult to retain. Despite harsh conditions, waiting lists to obtain a lot were long.

Population grew at annual rates of 3–4 percent throughout the Brazilian Amazon in the 1960s through 1980s. Growth rates in most areas slowed over time, with the migration component dropping off sharply during hard times in the late 1980s, as the government tightened subsidized credit and slowed road building as well as the opening of vast settlement projects (Lele et al. 2000). Populations occupied areas targeted for development and spilled over into areas not specifically designated for settlement. The frontier states of Acre and Rondônia saw staggering changes, with positions of relative populations reversed amid dramatic population growth. At mid-century, Acre's population of 100,000 was nearly three times Rondônia's 36,000. By 1996, Acre's population had grown fourfold, but Rondônia's population was nearly three times that, or 1.2 million. The major rural actors in both states consisted of large-scale interests (usually ranchers), extractivists, and small-scale, principally family, farms. Rural population continued to grow into the early 1990s in Rondônia, but it stayed roughly stable from 1970 in Acre, as urbanization offset in-coming rural migrants. By the early 1990s, both states had urbanization rates of close to 60 percent, part of broad growth in cities throughout the Amazon (Browder and Godfrey 1997). Amid these demographic, infrastructure, and economic shifts, the attractiveness of floodplain agriculture with access to river transport faded.

Upland agricultural areas rimming the Amazon forest, including south-central Rondônia, became more dynamic and diversified.

Although variation in deforestation estimates persists across sources due to varying techniques (see Faminow 1998 for a comprehensive look at the issues, the sources, and measures), deforestation to date is estimated to have removed roughly 13 percent of the Brazilian Legal Amazon's original forest cover. It has occurred principally along an arc varying in width from 200 to 600 kilometers, spanning the southern edge of the region and moving northward, with more than 80 percent within 50 kilometers of a major road (Lele et al. 2000). Approximately 152,200 square kilometers of forest were felled by 1978, although close to 64 percent of this was felled prior to 1960 (and grew back as secondary forest). This old deforestation was concentrated in the two states of Maranhão and Pará. By 1988, a decade later, about 377,600 square kilometers total had been felled (Faminow 1998). Area of forest felled continued to increase each year during the 1990s, with reports of a surge in 1994 and 1995 (Lele et al. 2000). Acre and Rondônia followed the general pattern seen for the Amazon as a whole. The result has been conversion of nearly a quarter of Rondônia's forests to agriculture, and just under a tenth of Acre's since the push to develop the Amazon began. Most of the cleared land is cultivated as pasture (70 percent in Rondônia and 80 percent in Acre) either immediately after clearing or, more often, after a cycle of annual crops for one or two years until yields drop off. Cattle herds in both states have grown dramatically, reaching approximately 3.5 million for Rondônia and 450,000 for Acre by the mid-1990s (IBGE 1998), even as soil degradation has limited pasture carrying capacity. Agricultural offtake is also substantial: rice production in 1995 topped 250,000

tons¹¹ in Rondônia and about 50,000 tons in Acre. Rondônia ranks third in Brazil among coffee-producing states with an output of 150,000 tons. Economic benefits and welfare improvements have accompanied rises in agricultural output following deforestation. Rondônia's per capita gross domestic product (GDP) grew by a factor of more than three (to about US\$6,500) and Acre's by more than four (to US\$5,700) in the 25 years after 1970, while both literacy rates and life expectancy have risen. By 1996, the United Nations Development Programme's (UNDP's) human development indices for both regions were drawing close to those for the rest of Brazil by 1996.

Economic growth has taken place against a macroeconomic policy backdrop in which inflation and hyperinflation of the 1980s—leading to fiscal tightening that included scaling back of Amazonian development—gave way to trade liberalization in the early 1990s, followed by an economic stabilization plan in 1994, strengthening the agricultural sector. Rising concern about loss of environmental services accompanying forest felling still on the rise each year and disputes over land as more economic activity moves into the area have led the government to undertake a number of forest-related policies. These include attempts to tighten restrictions on deforestation on private land (50 percent was the legal limit during this study) as well as establishment of national parks, extractive reserves, and indigenous reserves amid new zoning initiatives, and initiating new environmental impact assessment requirements. The vast area involved and lack of training impede enforcement of government forestry regulations, as do, according to one World Bank study (Lele et al. 2000), competing objectives, lack of tailoring to different local con-

ditions, and few market-based incentives. There is, moreover, growing awareness that if regulations were followed, additional land available for agricultural expansion is fast diminishing, but policy requirements for economic growth from agriculture are not (Soares 1997). This is in part behind important shifts in agricultural research emphasis in the Amazon. Farm-based research has swung from a focus on higher yields on specific, traditional food crops to emphasis on higher returns from a portfolio of agricultural activities. Research now includes a larger agroforestry or pure forestry component alongside more long-standing initiatives on pastures and annual crops. Efforts are made to assess and improve likely economic and environmental impacts of research from the design phase (Valentim and Vosti forthcoming).

Even as policy debates and changes proceed, new forces are at work increasing pressure on Amazonian forests. Robust domestic timber demand and exhaustion of forest in Southeast Asia mean logging, determined to be a less important factor in Brazilian Amazonian deforestation than small-scale agriculture a decade ago, is growing more significant (Lele et al. 2000; Reis and Margulis 1991). The role of small-scale agriculture is also changing: as agricultural production from older settlements continues to expand, new areas are being opened up to small-scale agriculture. Within the last five years, government response to a growing landless movement in Brazil has sparked a new wave of settlements in the Amazon, including in Acre and Rondônia. There are fewer migrants this time, and they are being settled into projects and on lots smaller in size than in the past, away from contiguous forest areas. New lines of credit more easily accessed have

¹¹In this report, all tons are metric tons.

begun to flow. Being able to understand and to some extent quantify the likely behavior of small-scale farmers in response to policy changes, and the consequences for their welfare, economic growth, and deforestation, is thus more important than ever. The next section briefly summarizes research on deforestation for agriculture in Brazil.

Research on Deforestation and Agriculture in the Brazilian Amazon

Deforestation rates in the 1980s—estimated at 20,000 square kilometers annually—brought international research attention to agriculture in the Brazilian Amazon. Pastures expanded quickly at the same time; studies later confirmed the importance of cattle ranching in Brazilian Amazonian deforestation (Reis and Margulis 1991). Policy analysis indicates that the substantial credit subsidies disbursed by the government to large ranching concerns to induce settlement of the frontier were responsible for agriculture's growing presence in the Amazon, and huge tracts of forest fell in the name of low productivity and extensive livestock production (Binswanger 1987; Mahar 1989). Because soils lose nutrients from the burn of forest biomass relatively quickly in cleared areas, it was thought that pastures would degrade quickly, forcing farmers to deforest more land to support existing herds; already high deforestation rates would therefore be sustained (Fearnside 1989; Hecht 1984). This was taken as evidence that cattle ranching in the Amazon without subsidies would simply not be profitable (for a critique of this conclusion based on different studies' models and assumptions, see Faminow 1998). Similarly, the low agronomic potential of Amazonian soils was thought to be behind deforestation by small-scale farmers who had moved to the region also in response to government incentives. Their need to plant annual crops for subsistence and their inability to pur-

chase inputs to keep a given plot in production more than a few years forced them to deforest more land, thus perpetuating a cycle of poverty and environmental degradation (Cunha and Sawyer 1997).

This implied that the Amazon was no place for agriculture, either small or large scale, given the low productivity, environmental damage, and the need for continued public sector support to persist. When federal support for settlement dwindled in the late 1980s (Lele et al. 2000), in response to domestic fiscal concerns and international criticism of Amazon policy, some expected that farmers would abandon their lots. Lower rural population growth and urbanization trends seemed to support this notion (Cunha and Sawyer 1997).

Early studies, however, overstated the decline in carrying capacity, particularly of pastures. They failed to account for the fact that farmers' situations vis-à-vis developing markets were improving over time and that practices and technologies better adapted to agronomic conditions would emerge over time (Faminow 1998). While not numerous, several studies from different parts of the Amazon now exist that take a careful look at production parameters and financial profitability of pasture and livestock production systems (Faminow 1998 summarizes these, and underlines the importance of dual milk/beef production systems for smallholders).

Other evidence emerged that called into question the conventional wisdom that agronomic constraints were principally why farmers continued to deforest. Pfaff (1997), for example, found that more deforestation occurred on soils of higher fertility. Profits for pasture systems persisted even with less government support (Faminow 1998; Faminow and Vosti 1998; Hecht 1993; Mattos and Uhl 1994; Valentim and Vosti forthcoming). While some have argued that intensifying pasture systems could remove pressure to deforest (Mattos and Uhl 1994; Arima and Uhl 1997), they did not always take explicit account of all farm resources

(Faminow 1998) or long-run effects. Cattaneo (2001a,b) finds that improvements in cattle technology promote deforestation in the long run. In general, he sees significant differences between short- and long-run scenarios, which indicate the importance for deforestation of free movement of capital and labor to and from frontier areas.

In explaining pasture expansion, Faminow (1997; 1998) argues that government support sparked burgeoning regional demand for livestock and dairy products, a factor usually overlooked, since most studies, especially those concerned with the environment, emphasize supply. Given the vast distances within the Amazon, and separating the Amazon from other livestock-producing areas, unmet demand creates powerful price incentives for regional livestock production. Faminow demonstrates how both production growth and regional movement of livestock goods conform to expectations from a spatial market analysis. Farmers in the western Amazonian frontier benefited from a price premium that allowed them to thrive without forcing them to significantly alter low-productivity, land-extensive technologies. Walker, Moran, and Anselin (2000) interpret regression results indicating that producer price changes favored beef over other cash crops in the Brazilian Amazon in the period from the mid-1970s to the mid-1990s. Schneider (1992) discusses, and Cattaneo (2001b) finds evidence for, the transference of livestock production to the Amazonian frontier as soybean production expanded in areas where livestock previously dominated.

Other work at the regional level emphasizes the combined role of expanding road networks and rising agricultural demand in prompting population growth and deforestation (see, for example, Pfaff 1997), while documenting some role for govern-

ment policy. Using county-level data, Pfaff (1997) confirms the importance for deforestation of some of the trends coming out of the policy push to develop the Brazilian Amazon: development projects were linked to deforestation in the 1970s but not the 1980s (but no robust relationship regarding credit emerged); closer proximity to markets to the south of the Amazon as well as higher road densities were associated with more deforestation; and early arrivals to the region—not simply higher population densities—had greater environmental impact.¹² Andersen (1996) similarly found that the importance of federal policy for deforestation faded in the 1980s in the face of local market forces—economic growth, population growth, and locally funded roads. Schneider (1994) argued that increased road density in already settled areas and fewer roads reaching into new forest areas are necessary to provide sustainable livelihoods for forest inhabitants, while protecting further encroachment into the forest. Some studies point to the importance of property rights in Brazilian Amazonian deforestation, including a role for land speculation (Alston, Libecap, and Mueller 1999; Kaimowitz and Angelsen 1998). Others discount the role of speculation. Chomitz and Thomas (2000) demonstrate a link between land values and expected profit streams from agriculture. Faminow (1998) shows that, in the decade from the mid-1980s to the mid-1990s, Amazonian land prices appreciated at far lower rates than elsewhere in Brazil, and relatively few opportunities existed for strongly positive returns (over 5 percent annually) from Amazonian land purchases. In a general equilibrium framework, Cattaneo (2001a) finds that insecure property rights tend to protect forests, but the size of the effects varies greatly with the length of security of tenure.

¹²This study did not, however, explicitly consider colonization projects.

Still others have found that climatic conditions, principally high precipitation levels, in effect prevent conversion of forest to agriculture (or promote abandonment of that land), even controlling for some market linkages, and that agriculture offers low private returns (Chomitz and Thomas 2000).¹³

Considerable uncertainty persists about the relative roles of large- and small-scale farming, in particular pasture operations, in deforestation (Lele et al. 2000). Faminow (1998) breaks down farm-size statistics by state, noting that Mato Grosso, the only state where smallholders are relatively absent, is where large-scale ranching predominates on land not originally forested, which suggests that smallholders play an important role in Amazonian deforestation. Walker, Moran, and Anselin (2000) find evidence from the eastern Brazilian Amazon suggesting that deforestation rates vary considerably with the history of original settlement of area, and they find disagreement between satellite images and farmer survey data. Fujisaka et al. (1996), however, find recall survey data from farmers generally in line with satellite imagery for one of the western Amazonian sites studied here. In his general equilibrium model, Cattaneo (2001a,b) finds that particular agricultural technologies have different impacts on deforestation, depending on whether small- or large-scale farmers adopt them.

Among those focusing on small-scale farming, there are mixed results regarding the welfare of migrants in settlement projects and deforestation there. Some found evidence that the welfare of settlers had improved from their areas of origin (Schneider 1994), and others found evidence of decapitalization (Jones et al. 1995). Leña (1991) describes a multiwave settlement process in

a colonization project in Rondônia, in which distress sales of lots by deeply indebted early migrants led to transfers of properties to second-wave migrants with considerably greater assets. Alston, Libecap, and Schneider (1995) similarly find settlers at the frontier to be poorer than those settling within the forest margin. They also find property transfers from farmers with low opportunity cost to farmers with higher opportunity cost as the frontier develops and rising land values accompanying land market development, which contributes to settlers' ability to capitalize. Dale et al. (1993) model the effects of farmer transience on land use in that same colonization project, given biophysical constraints on agriculture and distance to market. At the household level, Dahl (1998) and Faminow et al. (1999) document how, up until the 1994 stabilization plan, households tended to choose pasture systems in part because of price risk. Walker, Moran, and Anselin (2000), in a regional study focusing on the eastern Brazilian Amazon, find that availability of hired labor trumps on-farm financial and family labor forces as a factor in smallholder deforestation.

Other deforestation studies examine land use choice in more detail from a farm-level perspective, comparing relative profits of alternative systems as well as farmers' ability to adopt them, and including qualitative analyses of policy impacts. In the eastern Brazilian Amazon, such financial analyses include de Almeida and Uhl (1995), Arima and Uhl (1997), and Toniolo and Uhl (1995). Some similar studies in the western Brazilian Amazon took a whole-farm view by including the opportunity cost of family labor alongside out-of-pocket expenses (for example, Vosti et al. 1998 for agroforestry systems and Faminow, Pinho de Sa, and de

¹³More precisely, on the basis of existing agricultural use, climate, and infrastructure for the Legal Amazon, they predict rapid drop-offs in the percentage of area in agriculture between 1,600 and 2,000 millimeters of rain annually (from 22 to 8 percent), with virtually no land in agriculture at precipitation levels of 2,300 millimeters.

Magalhães Oliveira 1996 for pasture systems). Faminow (1998) also describes cattle services (such as banking, traction, organic matter, and cultural considerations) that are often overlooked in financial analyses but make these systems especially attractive to smallholders. Jones et al. (1995) use a regression framework to study farm-level choice of pasture versus other land use options for an Ouro Preto do Oeste, Rondônia, sample in the western Brazilian Amazon. They find higher productivity per hectare associated with lower levels of forest clearing, with a stronger effect for crop than pasture productivity—perhaps picking up effects of labor-intensive technologies used in perennial production. These studies and others at both national and regional levels in Brazil (including Cattaneo 2001a,b; Walker, Moran, and Anselin 2000) may point to labor availability as a critical factor for small-scale farmers that affects land use choice and, in turn, deforestation.

Objectives

This report sets out to examine the policy issues regarding environmental sustainability, economic growth via agriculture, and poverty alleviation presented by the presence of large groups of smallholders practicing semi-subsistence agriculture at the edge of Brazil's Amazon rainforest. The aim is to provide concrete information to decisionmakers and all who are interested in striking a balance among these objectives. More specifically, the report seeks to

- examine the trade-offs or complementarities under current conditions between farm household welfare, including prospects for rising out of poverty where this is relevant, and effects on the environment felt beyond the household,

focusing on loss of privately held mature forest in these areas;

- highlight how prospects for forests and farm-level welfare might shift under proposed or imminent changes in situations faced by farmers (as a result of policy changes or other factors);
- explore the latitude for policy action—particularly combinations of policies that involve consideration of available agricultural technologies and existing local institutions—to improve farmer welfare and environmental outcomes on farms; and
- discuss the generalizability of findings and methods beyond the study area, drawing implications for other forest margins where possible.¹⁴

To illuminate these topics, the report takes several sequential steps, each stemming out of a common underlying theoretical model of household behavior under constraints centering on profit maximization after making some assumptions about household preferences and consumption patterns. The model is dynamic in nature, forward-looking regarding profit expectations and time paths for optimal action, backward-looking regarding resource constraints resulting from past actions, and captures the agility with which farmers can react to price signals given land use conversion techniques and ongoing biophysical processes. The model centers on the importance to household land use decisions of household endowments of labor, knowledge, liquid assets, and land (including land quality and the previously mentioned biophysical processes) plus specifics of the market/institutional context, especially available technologies, but also marketing structures and nonmarket (or what could be

¹⁴It does *not* involve identifying a socially optimal level of or locale for deforestation but aims to provide input to policymakers who face such choices. Nor does it attempt to explain the process by which smallholder agriculture came to the Amazon—a topic best explored beyond the farm level.

seen as a market formed at a more local, informal level) opportunities for trading among neighbors. These factors combine to form prices that households see at the farm gate, or prices in effect internal to the household because of on-farm competition for scarce resources—for inputs and outputs upon which households base their production decisions, including land use. More detail on the theoretical model appears in each analytical chapter, with different simplifying assumptions made in each case to examine different aspects of the problem using different analytical tools.¹⁵ With this model as a backdrop, the report undertakes to meet the objectives in four discrete steps.

The first step is to describe trends in the study area, not just in land use and welfare, but also in factors that might affect them, notably household, farm, and off-farm market and other institutional characteristics. This description provides an understanding of the context in which land use decisions are made, including important heterogeneity, and possible “success stories” in the sample (farmers whose livelihoods are improving at less expense to the forest). This information is important in its own right as input to policy decisions but critical as a basis for developing and understanding the rest of the analysis.

The second step is to assess, of the myriad possible determinants of land use trends, which are most essential in these particular study sites and with what implications for livelihood, poverty, and environmental aspects of interest.

The third step is to explore implications of these key determinants for policy, outlining likely outcomes if current conditions persist, possible ones given current policy debate, and, perhaps most importantly, the

scope for policy to make success stories more prevalent.

The fourth step involves an attempt to pin down when and how the types of key determinants and their relationships with land use decisions hold in other settings. This is done with an eye toward whether a similar type of analysis, if performed elsewhere, would need to have the depth required in this one. Could it be pared down or could the emphasis of the hypotheses (and therefore the analytical technique and data requirements) be shifted? More efficient research methods are required if the number of micro-level studies for various developing-country settings needed in order to understand broader deforestation processes at work have a hope of being undertaken by researchers. (See the earlier discussion on the lack of micro-level empirical studies providing a foundation for work at broader scales in diverse settings.) The need for research efficiency is, if anything, more pressing for developing-country researchers, who are often under severe resource constraints.

Methods

The report uses a mix of descriptive and analytical methods and tools to cover the ground required by the four steps described above. Underpinning all the analyses is descriptive information about how farmers use land, derived from a mix of primary and secondary sources. Secondary data on prices and aggregate land use trends are supplemented with information about farming practices, available and experimental technologies, land tenure processes, marketing channels, and functioning of local organizations gleaned from both formal surveys and informal interviews with

¹⁵The model does not account for endogenous changes beyond the household driving development of new technology or general equilibrium effects, if any, that emerge when individual households like the one described here are jointly considered in one study region. Both aspects, however, and their possible implications for analysis, are discussed within the analytical chapters.

farmers, extension agents, representatives of government entities (including agricultural research) at the local level. Primary data on household land use, endowments in labor, capital and land, and market access were obtained in two rounds of survey data collection at the two project sites; 1994 and 1996 were the primary field survey years, although data were collected from about 1993 through 1997. Primary data on local characteristics were obtained via a mix of household and community surveys, plus a separate survey and interview technique focusing on local organizations (Sydenstricker 1998 summarizes findings from this last survey).

This information documents current trends in farmer welfare and land use. Key determinants are identified via a mixture of analytical techniques. Farmer adoption of particular technologies is first analyzed in a policy analysis framework that combines financial analysis (private returns to land and labor) with assessments of factors both on and off the farm that might affect adoption in a realistic setting. Profitability and adoption assessments are based upon qualitative judgments about profit risk, especially from production, price, and marketing channel volatility. The framework is conceptually dynamic, focusing on a land use trajectory for a particular plot rather than taking a static one-period view. Its strength is its ability to focus in on the importance of factor intensities and the resource base in the performance of particular technologies over a time horizon. The assessment of on-farm resource constraints, principally labor and capital, is based on primary data. The more qualitative assessment of aspects of local markets and institutions that might facilitate or impede adoption emerged from participatory interviews with researchers, extension agents, and farmers.¹⁶

Multivariate regression analysis is used to highlight factors that are specific to farms, farm households, or their access to markets or trading opportunities and that affect observed patterns of land use by exploiting the heterogeneity in these dimensions found in the sample. While important factors behind observed patterns—such as risk, exact consumption patterns, or farmer knowledge—cannot be directly tested for given data constraints, they nonetheless are a part of observed land uses, a fact that needs to be considered in interpreting regression results. More specifically, the equations to be estimated are derived from the theoretical framework of household profit maximization, constrained by fixed land quality and limited labor and capital resources resulting from incomplete access to regional markets. It explores the respective roles of heterogeneous household and farm characteristics, on the one hand, and local policy, institutional, and market characteristics, on the other, in changing prices faced by farmers from those formed at the local marketplace. It does so while controlling for land quality and factors—principally biophysical, in the absence of external input use—that impede swift conversion from one land use to another in response to farm-gate and endogenous prices. Although a cross section, it encompasses some essential dynamics of the problem of choosing an optimal time path of land use based on expectations of future profits, subject to biophysical and other resource constraints as well as local institutional (including market) characteristics. As applied, the model estimation captures more of the backward-looking elements of this dynamic problem, drawing on panel-type data for recent land uses as well as the state of the lot when the current owner arrived.

¹⁶This participatory process alone proved useful and sometimes eye-opening to the various categories of interviewees about aspects of technology development and design they had previously not thought or known much about.

A farm-level bioeconomic linear programming model, also derived from the basic theoretical structure, highlights the roles of on-farm resource competition and the forward-looking aspect of farmer profit maximization to provide important angles needed to identify key land use determinants lacking in the other analytical tools. It incorporates important biophysical aspects into the dynamic framework, namely the role of nutrient availability in on-farm competition among specific land uses, as well as degradation processes resulting from (or continuing in the absence of) particular land uses. It also allows more explicit consideration of the role of relative prices, both exogenous to the farm and endogenous, in the case of imperfectly traded goods, since these enter the model explicitly. The bioeconomic model explores these aspects under some assumptions about basic farmer, farm, and institutional/local contexts that are held fixed for specific scenarios that run out over a 25-year time horizon. The assumptions, including prices, are themselves derived from fieldwork and the other analyses or secondary data sources already discussed (and changeable to reflect the range of conditions in the sample and to examine their implications). Caveats about how far the model can reliably be tweaked are explored in the chapter on the model. Analyses for identifying determinants of land use also point to specific roles for welfare/farmer income as both determinant and outcome of land use decisions.

All analyses discussed thus far seek to understand current conditions and processes, and the report explores policy implications of the findings associated with specific research results, which suggest

possible farmer responses to specific policy changes. To gain insights into a wider range of situations, a means of exploring counterfactual or future scenarios is needed. The bioeconomic model stands alone among the analytical tools used here in this regard, via its ability to shed light on the forces that would affect farmer response to a range of different conditions (with caveats as already alluded to) and policy contexts. The simulation tool is used to highlight farmer responses, under otherwise current conditions, of particular changes in policy or socioeconomic environment. The aim here is less to predict likely future paths than to further highlight the nature of on-farm resource competition and dynamic profit maximization, with biophysical processes more realistically integrated into the process than is often the case.

The fact that this sample included two study sites and heterogeneity within each expands the ability to generalize from results, compared with a pure case study. And, to some extent, bioeconomic model simulations provide clues for what could happen in other forest margin areas like the ones studied here. Still, empirically based lessons for other forest margin areas cannot realistically be drawn out of the sample, but the body of evidence emerging from the conjunct of analyses combined with knowledge of the study setting and presence of a broader theoretical framework contributes to informed speculation on this topic. That said, sufficient detail on all analytical tools used here is documented or cited in this report to allow their replication in other settings.¹⁷

¹⁷Other tools or variants of these are available that could also cover the steps outlined. Some of them (such as spatial regression analysis or spatially explicit bioeconomic modeling, time series analysis, or a longer panel of data) could be important for understanding the processes under study but require a level of detail and amount of data that made them untenable here. Based on findings in this report, the spatial analysis could be particularly illuminating if it incorporated local processes not explicitly modeled here but to which this analysis points as important.

Organization of the Report

Chapter 2 describes the research sites and the household sample on which analysis is based. It provides historical background on the study sites. It then characterizes prevalent land use patterns—cross-sections of land cover plus trajectories of the evolution of plots from forest to various land uses over a 20-year timeframe—as well as current and proposed production technologies. It does so within the context of available household resources, market access, and nonmarket institutions, describing those sample characteristics in the process. Chapter 3 includes in more explicit form the general theoretical (dynamic) model of optimal land use under the constraints described. It derives reduced-form (cross-section) land use equations from the theoretical model to be estimated in a multivariate regression (Tobit) framework, then presents

and discusses specific hypotheses and results. The analysis explores the respective roles in land use of heterogeneous household and farm characteristics, on the one hand, and local policy, institutional, and market characteristics, on the other. Chapter 4 lays out the structure of the bioeconomic linear programming model, presents land use and income results over a 25-year time horizon for a baseline scenario (continuation of current conditions), explores the sensitivity of results to changes in key parameters, and describes land use and income results for a series of policy scenarios relevant to the study area. Analytical chapters contain separate sections on assumptions and their implications for results. Chapter 5 presents principal conclusions and implications for policy and future research.

CHAPTER 2

Research Site and Sample Characteristics

This report focuses on two colonization projects along the main roadway, the BR-364, that links the western Brazilian state of Acre to its neighbor to the east, Rondônia, and Rondônia to the south of Brazil. Figure 2.1 locates the projects Theobroma and Pedro Peixoto, and their respective states, Rondônia and Acre, within the western Brazilian Amazon. This chapter describes the research site, land use patterns in the study area, selection of the household sample, and sample characteristics.

Site Description

The all-weather BR-364 allows flows of goods, services, and people to reach these remote states in the western Brazilian Amazon from major markets in the south around São Paulo. Built in 1968, it initially linked the south to Porto Velho, Rondônia's state capital and a major port on the Rio Madeira, providing access to the Amazon for streams of migrants throughout the 1970s. The intensive colonization accelerated even more in the early 1980s, after the road was paved. The state government in Rondônia has at times actively promoted particular agricultural products and livestock through rural credit programs. Farm establishments statewide ballooned, rising from about 1.6 million hectares in 1970 to about 8.9 million hectares in 1995 (IBGE 1998; Silva Filho undated), with farms of 10–100 hectares contributing 46 percent of state agricultural GDP (IBGE 1998). In more settled Acre, extractive activities (principally rubber tapping and Brazil nut collection) were already a tradition when the opening of colonization projects accelerated in the 1970s. Because Acre's links to southern markets and even Rondônia were more tenuous and further away (the stretch of BR-364 between Porto Velho and Acre was only paved in the early 1990s), its inflow of migrants was somewhat muted (Avila 1994; Carvalho de Mesquita 1996). Government policy and discussions on Acre have often centered around a development strategy involving forest products. In sharp contrast to Rondônia, Acre started from a larger farmland base in 1970 of 4.1 million hectares, peaking near 5.6 million hectares in 1980 (IBGE 1998). At the end of 1995, farmland stood at about 3.2 million hectares (IBGE 1998), as agricultural activity shifted from the far western reaches of the state eastward toward the state capital of Rio Branco near the border with Rondônia (Acre 2000).

While the two states have been subject to contrasting pressures for agricultural expansion as a result of differences in policy and market environments, both have seen a pattern of private forest falling and pasture area rising over the two-and-a-half decades since colonization began in earnest. Even though absolute area in forest on farms in Rondônia grew five-fold from 1970–95, the proportion of farms in natural forest dropped from about 66 percent to nearly 57 percent during the period, as planted pasture grew from 2 to 29 percent of farm area

Figure 2.1 Map locating Theobroma and Pedro Peixoto in the states of Rondônia and Acre



(IBGE 1998). From a less dramatically changing area base, Acre evinced similar patterns starting out with higher proportions of farmland in natural forests. Acre farmland went from close to 95 percent forested and less than 1 percent in planted pasture in 1970 to 73 percent forested and nearly 18 percent in planted pasture in 1995 (IBGE 1998). In both states, the amount of forest cleared has increased with each passing year. As in the rest of the Amazon, both 1994 and 1995 saw large increases in volume variously attributed to poor data because of cloud cover on satellite images to incentives to invest more in forest clearing in the wake of the July 1994 currency stabilization plan (Lele et al. 2000).

For this report, sites within these two states were chosen to examine the contribution to these land-use trends of one type of land user in one type of area—small-scale farmers in government-sponsored colonization projects—amid different policy and market settings. From 1970 through 1999, settlement projects in Rondônia numbered 96, spanning close to 5 million hectares, with close to 50,000 families settled. Over time, the area of each project has tended to shrink (and with it initial lot size distributed), and lower proportions of project area are formed from unowned, natural forestland (Ferreira 1996; S. Oliveira, personal communication). Likewise, by 1999, Acre had 53 settlement projects, covering nearly 1.3 million hectares, or 9 percent of the state, with over 16,000 families settled (Acre 2000). Although insufficient data exist for precise measurements of state rural areas and calculations of rural population densities, illustrative ranges for both states in 1995 show that these densities were still low. Statewide population densities (using rural and urban populations and total state area) that year were approximately 3.2 people per square kilometer in Acre and 5.2 people in Rondônia. Distributing the rural population over the entire state area (underestimating the desired figure), then over all farm area established within the states

(overestimating the desired figure) results in ranges of 1.10–4.21 and 1.96–6.24 people per square kilometer for Acre and Rondônia, respectively (IBGE 1997).

The colonization project of Theobroma, Rondônia, is located some 350 kilometers south of Porto Velho along BR-364, and it spans approximately 300,000 hectares, much of which was spontaneously settled well before the project's official opening in 1979, with approximately 3,000 families settled on 100 hectare parcels (Fujisaka et al. 1996). Pedro Peixoto, Acre, lies some 500 kilometers to the west of Porto Velho along BR-364, with its center about 60 kilometers east of the Acre state capital of Rio Branco. Opened in 1972, it covers approximately 317,600 hectares and is officially home to 4,225 families (Acre 2000). These projects were chosen because of their differences in amount of forest cleared (more than half in Theobroma, less in Pedro Peixoto), land use (perennial tree crops being more evident in Theobroma), soil degradation (more advanced in Theobroma), time since initial settlement (Pedro Peixoto is more recently settled), population pressure (higher in Theobroma), policy environment, and access to markets (Avila 1994). While Rondônia has soils of generally higher fertility and flatter topography than Acre, Theobroma has relatively poor soils; it was selected to enhance the capacity to control for the importance of this factor across policy settings.

Agriculture in the Study Area

This humid tropical area of the southern Amazon rainforest sees temperatures averaging 22–60°C and mean rainfall of about 2,000 millimeters annually, with a heavy rainy season from October through February, sporadic rains through May, and a marked dry season from about June through September (Fujisaka et al. 1996). While soil quality varies widely and is patchy, predominant soil types—Oxisols in Acre,

and Oxisols, Alfisols, and Ultisols in Rondônia (Fujisaka et al. 1996)—are of relatively low natural fertility with high levels of acidity, low phosphorus content, low levels of cation exchange, and high levels of aluminum toxicity (Sanchez 1976; Palm, Swift, and Woomeer 1994).

The distinct dry season permits agriculture by a slash-and-burn process (contrasting with the slash-and-mulch system adopted in more humid Amazonian areas, described in Pichón 1997). A typical agricultural year starts in May with the beginning of the dry season and finishes in April, the end of the rainy season. Forest-felling occurs during the dry season from May to July. The cleared area is allowed to dry, then burned in August or September prior to the expected onset of the rains, and planted to annuals, perennials, or pastures.

Slash-and-burn agriculture exchanges the relatively efficient and continuous nutrient cycle of the forest ecosystem for a one-time transfer of the stored forest biomass to the soil. The biomass and its litter are sources of organic inputs; once they are on the soil, they decompose to generate plant-available nutrients and soil organic matter. In the first year after the burn, annual crop yields are good, benefiting from the nutrients in the forest biomass, which lower soil acidity from the ash and make it more available to the crops. Afterward, crop uptake occurs at planting time and the cropping system releases its litter (crop residues and roots decay) at harvesting time, a process that generally causes loss of nutrients if no fertilizer is added. Agroforestry and pasture systems, when managed properly, come closer to replicating the nutrient flow of the forest system and thus use nutrients more efficiently than annual cropping in the tropical conditions (Palm, Swift, and Woomeer 1996 discuss soil organic matter and agricultural productivity).

The nutrient depletion process underlying land use in the Brazilian Amazon is a slow but steady march from forest to pasture, perhaps through a succession of land

uses along the way. Most farmers plant annual crops in the first year, usually rice alone or rice intercropped with corn, followed by a second crop of beans. Many plant manioc in the second year (Fujisaka et al. 1996). Food crops are supplemented by corn to feed chickens and pigs raised around the house, which provide the family with extra protein.

With use of fertilizer virtually nonexistent in the study area, yields decline rapidly after the second year and annual crop production on a given plot is usually abandoned after the third year. The plot then either goes into a fallow period of several years of secondary forest regrowth (“fallow” in the rest of this report implies such regrowth; in practice this period is almost always less than the five years required to recover a level of nutrients similar to that seen in forests). This is followed by another year or so of annual crops, or the land is planted to perennial crops—usually bananas or coffee (less prevalent in the Acre site). More frequently, however, the land becomes pasture. Perennials or pasture may be intercropped with a final year of annuals (annual/perennial intercropping in fact indicates that perennials are in an establishment phase).

Perennials must grow for several years before bearing fruit; replanting must occur about every eight years. Pastures take a year to establish, are usually burned yearly for control of weeds and pests, and also must be replanted, but at intervals that depend on several factors. The pace at which pastures degrade depends on soil type, pasture maintenance, stocking rates, quality of the forest burn, frequency of pasture burning, and variety of pasture grass planted. Livestock activities may focus on milk or beef production, usually dual purpose, although the 1996 agricultural census reported a resurgence of pasture production of beef alone in both Acre and Rondônia (IBGE 1998). As yet in this study area, there is little specialization in breeding or fattening (as opposed to trends reported by

Toniolo and Uhl 1995 in the less land-abundant eastern Amazon state of Pará).

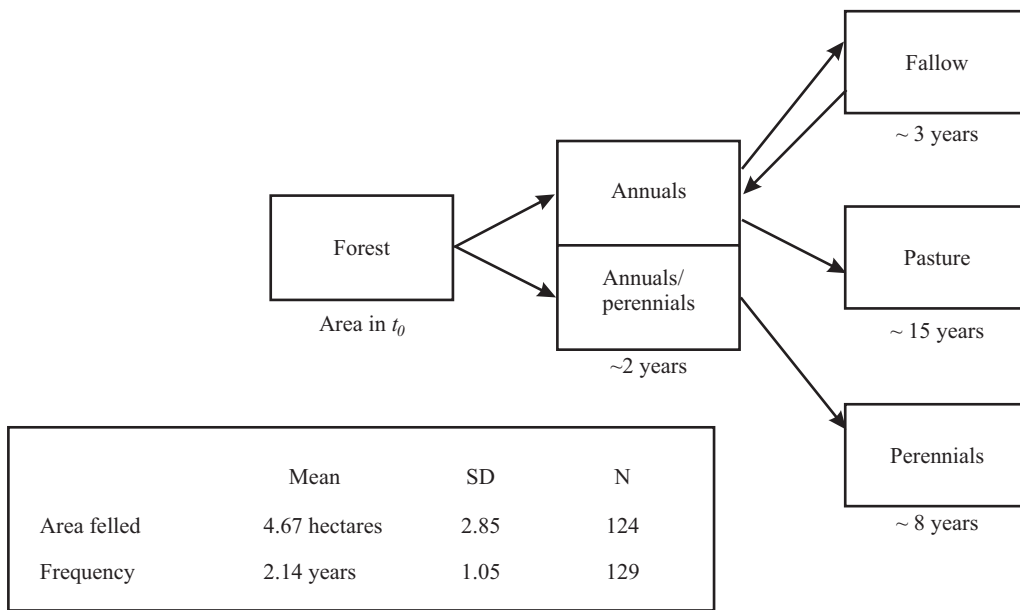
Figure 2.2 sets out the land use trajectory of a plot of land from forest, highlighting the number of years that different aggregate land uses usually remain on farmers' fields. The figure also notes the observed periodicity of forest felling and average size of plot felled in the projects. Private lots are usually deforested from the front of the lot (facing the road) to the back, with area in pasture steadily accumulating (Fujisaka et al. 1996).

Virtually all farms include a home garden, located near the house, with some annuals and fruit trees. In Acre in particular, some households collect Brazil nuts from remaining forest areas, or hunt, fish, or

gather medicinal plants there. Valuable timber was selectively logged in both study areas before initial settlement, and timber extraction is not now a major activity in these study areas. Income from the aforementioned activities can be supplemented by engaging in on-farm processing of primary products—processing manioc flour, making cheese, or aquaculture, for example.

With few farmers using herbicides and pesticides, and fewer still applying fertilizers, most crop yields for Acre and Rondônia remained low and roughly stagnant in the decade 1985–95.¹⁸ For the 1995/96 agricultural year, statewide yields for rice were 1,100–1,200 kilograms per hectare; for beans, 500–600 kilograms per hectare; for

Figure 2.2 Land use trajectories and deforestation



Notes: The number of years noted below each land use box indicates time continuously in a given land use and not the time elapsed from t_0 .

corn, 1,200–1,300 kilograms per hectare; and for manioc, 8,900–10,000 kilograms per hectare (IBGE 1998). With the exception of manioc (which saw an increase in area from 8,202 to 13,892 hectares over the decade), area devoted to these crops in Acre stayed relatively stagnant over the decade, varying up or down by little more than 1,000 hectares. In Rondônia, however, area devoted to rice and manioc fell by nearly 50 percent, to 79,000 hectares and 5,000 hectares, respectively, while coffee area expanded from 67,000 hectares to 97,000 hectares (IBGE 1998).

Stocking rates rose substantially in both states over the decade 1985–95, based on reported pasture area and bovine herds. In Rondônia, the change was from 0.88 to 1.56 animals per hectare, and in Acre from 1.30 to 1.53 animals per hectare (IBGE 1998) (these figures do not account for herd demographics, which would mean lower rates in terms of animal units). These rates go beyond what local agricultural researchers deem appropriate carrying capacity, and beyond what Chomitz and Thomas (2000) calculate from the same census for the entire Legal Amazon, with 40 percent of pasture having up to 0.50 animals per hectare, and the remaining 60 percent averaging 0.95 animals per hectare. As early as 1989, Valentim reported an estimated 70 percent of the then 600,000 hectares of pasture in Acre had over 25 percent weed invasion with some pasture returning to a secondary forest state.

The end of the decade 1985–95 included the first production year following a stabilization plan (in July 1994), which introduced the *real* as currency and effectively ended a period of high inflation and multiple changes of currency. The 1994/95

agricultural year also saw relative prices moving sharply in the direction of coffee production, compared with 1993/94 (trends are examined more fully in Chapter 4 on the bioeconomic model, since the two years of data collection spanned this period; see the section on the household sample in this chapter and Table 4.4 in Chapter 4).

Agricultural research has developed some experimental production systems to improve yields that have been sporadically adopted in the study area, including coffee intercropped with fast-growing timber species for Rondônia, and pasture mixed with nitrogen-fixing legumes—ground cover that reduces weed invasion and removes the need for yearly burning, while improving the nutrient content of pasture for cattle—in Acre. Other higher-yielding systems are more experimental still (and yet to be adopted). Improved fallow systems involve purposeful planting of tree species in fallow areas that increase nutrient value each year the fallow forest grows back, resulting in the possibility of earlier cuts requiring less manpower. Sustainable timber extraction systems center around low impact extraction methods for species with some economic value using a 40-year rotation/grow back involving contiguous forests on private lands of groups of farmers. Extension agents in the area lack the resources to reach many farmers, but sometimes make arrangements to meet with groups of farmers who have organized in producer associations. At the same time, the flow of information needed for technology adoption may be hampered by the scarcity of time and money for forming and joining associations and by the dearth of local schooling and health facilities in the area (Sydenstricker 1998).

¹⁸All figures in this paragraph come from single-year agricultural censuses and are not time averaged; no data were available for multiyear smoothing to net out the effects of year-to-year variations in recorded output due to risk factors.

All systems, but especially traditional and experimental perennial and pasture systems, require some upfront investments before cash income flows, yet farmers do not have easy access to formal credit. The 1996 agricultural census confirmed that about 2 percent of farm establishments in Acre and 3 percent in Rondônia received credit that year, and sources of informal credit are limited. Production systems also vary in their labor requirements. The conversion of forest and fallow land to cleared area is one of the most labor-intensive agricultural activities, all done by adult males with chainsaws or scythes. Perennial trees also require a considerable amount of labor seasonally, particularly for the harvest, especially in contrast to the low labor needs of extensive pasture systems. Women and children participate in some agricultural activities such as planting, harvesting, and gathering Brazil nuts. Adult male household members occasionally work off-farm for wages or in-kind payments of food or days of traded labor or a combination of the three.

Table 2.1 evaluates factors affecting smallholder adoption of selected traditional and experimental systems, including private profitability, labor requirements, and market and nonmarket institutional constraints. It is adapted from a broader framework that includes evaluation of agronomic sustainability of the system (principally export of nutrients), carbon balances, above- and below-ground biodiversity developed for cross-country application as part of the ASB program. (Working group reports summarize the methods used to fill each column of the ASB matrix: see Vosti et al. 2000 for socioeconomic data, Palm et al. 2000 for carbon data, Gillison 2000 for biodiversity data, and Weise 1998 for agronomic sustainability data). For application and more detailed discussion of the full matrix, see Gockowski, Nkamleu, and Wendt 2001 for sites in Cameroon, Tomich et al. 2001 for sites in Indonesia, and Vosti et al. 2001b for these Brazil sites.

Each row in Table 2.1 represents a land use system that is a *trajectory* of land uses over a 20-year period, usually beginning with a two-year cycle of annual cropping after forest is cleared, culminating in the land use system described by the row title. Each stage in the stylized land-use trajectory in Figure 2.2 is represented. For those systems not currently practiced for this length of time—for example a traditional annual/fallow system—the system is replicated over a 20-year period to shed light on why these systems have disappeared from the landscape (and enable cross-system comparison of results). This “unit” of analysis captures an aspect of land use patterns critical for the area but often overlooked in cross-sectional or activity-specific analyses: the importance of the time path of land use in the area, given serious agronomic constraints that themselves change with land use choices, and a propensity of the land cover to change—via invasion of weeds or return to secondary forest fallow—in the *absence* of timely management (Cattaneo 1998).

The environmental impacts of the systems (reported and discussed more fully in Vosti et al. 2001b) are based on carbon stocks averaged over the life of the trajectory, and biodiversity measurements (species counts, but with tallies kept of function in the ecosystem and whether species were productive or damaging to agriculture) for the principal land use in the trajectory. Details of methods are presented in Palm et al. 2000 and Gillison 2000, and details of site-specific findings in Lewis et al. 2002. Samples from the study area indicate forests average 220 tons per hectare in total carbon sequestered above and below ground, with the above-ground component (about two-thirds of the total) diminishing substantially for other land uses, least so for an aging fallow secondary forest. Biodiversity counts show a similar ranking of land uses (although degraded pasture area had considerably higher biodiversity than its

Table 2.1 Evaluation of land use systems

Land use systems (scale of operation)	Profitability ^a		Labor requirements ^b	Institutional requirements/constraints ^c	
	Returns to land (Reals/hectare)	Returns to labor Reals/person-day	(Person-days per hectare per year)	Market	Nonmarket
Forest	-2	1	1	...	...
Managed forestry (40 hectares)	416	20	12	Input, output, labor, and capital markets	Information, regulation, and social cooperation
Traditional pasture (75 hectares)	2	7	11	Input and output markets	...
Improved pasture (75 hectares)	710	22	13	Input, labor, capital markets	Information
Annual/fallow (1 hectare)	-17	6	23	Labor markets	Impact of local environment
Improved fallow (1 hectare)	2,056	17	21	Labor markets	Information
Coffee, bandarra (5 hectares)	1,955	13	27	Input, output, labor, and capital markets	Information
Coffee, rubber (5 hectares)	872	9	59	Input, output, labor, and capital markets	Information

Note: Land use systems are described in Vosti et al. 2001b. All involve a 20-year sequence of land uses from forest, beginning with a couple of years of annual cropping. For coffee-tree systems, socioeconomic indicators are based on production figures for each component, unaffected by competition. Effects of plant competition on productivity over time are not yet known but are under study in the area.

^aPrices are shown in December 1996 reals; US\$ = R\$1.04 (the approximately 1:1 relationship mentioned elsewhere in this report); discount rate used was 9 percent.

^bBold indicates competition, for a typical household, for labor with other agricultural activities including deforestation.

^cAssessments were made in participatory sessions with local researchers, extension agents, and farmers. Categories indicate institutional constraints to, or impacts of, adoption (with bold indicating a more serious problem).

well-managed counterpart, thanks to weed and pest invasion).

Economic evaluation is done from the perspective of a small-scale farmer with relatively good market access in the study area, considering local labor availability (project population densities in terms of

adult labor equivalents estimated in Vosti et al. 2001b to be approximately 3 to 4 labor units per square kilometer). Economic valuations are reported on a per hectare or per labor unit basis; prices are based on secondary data for local markets and a discount rate of 9 percent. Scale of operation is

included to give an idea of the size of plots normally dedicated to these activities in the study area. Institutional evaluations are the result of a participatory process including local researchers, extension agents, and farmers. Traditional and experimental systems are grouped by principal land cover to ease comparison of the gains they could embody; traditional systems are italicized to highlight relative profitability of land uses most widely observed.

Systems widely practiced are not the most profitable, strictly speaking. They tend to be the ones that have relatively low labor requirements; they string out capital establishment costs over time and their returns to labor hover near the prevailing market wage. (Brazil nut extraction is principally done by female laborers, so the market wage does not accurately reflect their opportunity cost. Since adult equivalents of labor are evaluated at market wage for the purpose of calculating returns to land, however, systems with real returns to labor under the market wage show a loss in terms of returns to land, but they would show a profit if only out-of-pocket costs were considered.)

This simple comparison is in keeping with local labor scarcity and limited credit access. It highlights the impact that imperfect labor and capital markets have on producer choices in the area. Relative labor scarcity and land abundance suggest that farmers will be particularly sensitive to returns to labor in adoption decisions. The 7 to 1 advantage in returns to labor for traditional pasture over forest extraction underlies the predominant land-use pattern of conversion of forest to pasture. Actual 20-year annual/fallow systems, while not much less profitable in terms of labor returns, have considerably higher labor requirements; this system is sometimes practiced on one plot at a time at the beginning of a land use trajectory that eventually ends in pasture or perennials.

All experimental systems yield considerably higher returns to labor than their tra-

ditional counterparts. Improved fallow and coffee-based systems, however, require labor commensurate with or beyond all family labor available to maintain 1 hectare of the system. While labor can also be hired in, farmers report that they are unable to do this to the degree they wish (in keeping with the low population densities of the area). These systems can only be implemented at scales of a few hectares at most without major influxes of labor to the area (Vosti et al. 2001b). Managed forestry, a system attractive in terms of economic returns and labor requirements, faces many market and especially nonmarket institutional obstacles to adoption. One obstacle is farmers' and technicians' need for information about which species are found there, which to extract, and with what methods and frequencies to ensure that extraction is sustainable. There are also considerable regulatory requirements and enforcement, virtually impossible to comply with in practice, to certify that timber extraction is sustainable or is coming from the portion of farms where forest felling is allowed. In addition, the system requires social cooperation at levels unusual in the area: a group of farmers must coordinate activities on contiguous forest areas to ensure a sustainable rotation over a 40-year cycle; and they must generate a volume of sawn planks large enough to interest local timber product merchants.

The improved cattle production system is likely to be among the most attractive to smallholders in that its financial performance is much greater than that of the traditional cattle system, and the market and nonmarket obstacles to adoption are fewest and probably easiest to overcome.

These experimental systems are analyzed because local researchers see them as promising candidates for sustainable intensification—improving livelihoods without serious damage to forests. The analysis of the trajectory of land uses for 20 years highlights sustainability concerns on both environmental and economic counts. In addition, the qualitative analysis of the

institutional environment reveals that each of the potentially most profitable and least environmentally damaging systems faces one or more institutional or other obstacles to adoption. The analysis, however, makes unrealistic assumptions about uniformity in availability and quality of inputs and management skills that would likely influence actual environmental and economic results. The adoption analysis, moreover, is done on a plot specific basis, ignoring farmers' allocation decisions based on their liquidity and labor constraints. The multivariate analysis in Chapter 3 and the bioeconomic model in Chapter 4 provide tools that allow analysis to focus on all land use choices simultaneously within producer constraints, and they relax the assumption of producer homogeneity without sacrificing two critical components of the analysis: incorporation of the importance of the dynamics of land use and the institutional context in which local farmers make decisions.

The next section describes the household sample and its characteristics, which provide the basis for evaluating farmer constraints to adoption and the underpinning for the multivariate and bioeconomic model analyses presented in Chapters 3 and 4, respectively.

The Household Sample and its Characteristics

A survey of 156 smallholder households within the colonization projects of Pedro Peixoto, Acre, and Theobroma, Rondônia, was designed and applied by researchers associated with the ASB Programme in late August and early September 1994.¹⁹ The survey detailed land use for the agricultural year 1993/94 (hereafter in this chapter re-

ferred to as "1994") and deforestation decisions; delved more deeply into specific production activities, commercialization of output, and off-farm income sources; and collected information on land use and tenure history, as well as household demographics, education, and migration history (Witcover et al. 1996; Witcover and Vosti 1996). A second, similar survey was administered during the agricultural year 1995/96 (hereafter referred to in this chapter as "1996") on 228 farms, 142 of which were visited in 1994. The production sections of the survey provided information that could be cross-checked against overall land use allocation and deforestation decisions; Fujisaka et al. (1996) found deforestation information from 1994 in agreement with satellite imagery about deforestation patterns.

Sample Selection

Households were randomly selected from a sampling frame that intentionally included variation in factors thought exogenous to farmers' shorter-term land use decisions: access to markets (proxied by quality of infrastructure, particularly in the rainy season), agricultural production potential of the soil resource base (derived from local soil maps plus expert knowledge), and time since initial settlement of lots in the subdivision of the project (Witcover et al. 1996; Witcover and Vosti 1996). So as not to exclude dynamics by which poor incoming settlers graduated to become more affluent medium-scale ones, farms larger than 100 hectares (up to approximately 200 hectares) chosen in the random selection process remained in the sample. Larger ranches were excluded. The sample expansion in 1996

¹⁹The survey team included representatives of Embrapa-Acre and Embrapa-Rondônia, as well as Centro Internacional de Agricultura Tropical (CIAT), the World Agroforestry Center (ICRAF), and IFPRI.

used a similar random selection process, this time purposefully including areas (at the edge of forests within projects) as yet not officially distributed by the land reform agency, which is the Instituto Nacional de Colonização e Reforma Agrária [National Institute for Colonization and Agrarian Reform], known by its Portuguese acronym INCRA. Sample attrition across the two years (about 20 farms) was primarily due to farms being sold “out of sample” to large ranches (two-thirds of attrition); the inability to find some farms and farmers who refused to be included account for the rest. Descriptive statistics in this section focus on the 1996 sample (228 households), occasionally drawing on the 1994/96 panel sample to emphasize trends, especially vis-à-vis land use.

Land Use and Deforestation

Average farm size was 81 hectares for the 1994 sample and 76 hectares for the 1996 sample (smaller because the latter included farmers newly settled by INCRA on lots, and because distributed lot size is shrinking over time, as will be discussed in more detail later). Figure 2.3 documents the conversion from forest to pasture of lots in the sample, based on recall data in the 1994 and 1996 surveys.²⁰ On average, holdings that were 88 percent forested upon 1996 owners’ arrival were only 61 percent forested in 1994 and 56 percent forested in 1996 (it is possible for the proportion of land in forest to rise if additional land is purchased). That average includes 35 percent of the sample that had less than 50 percent of their operational holding in forest and 10 percent with less than 25 percent still in forest. Pasture, on the other hand, grew from an average of 3 percent of the land upon arrival, to 21 per-

cent in 1994, to 27 percent in 1996. Between 1994 and 1996 alone, at the household level, forest area dropped by a mean of 7 percent of the operational holdings, while pasture area rose by 10 percent, with a slight expansion in area in perennial systems, perhaps indicating a response to the changes in relative prices discussed above. Land use patterns in 1996 for farms initially settled at different times (or different “vintages” or ages of farms in Figure 2.4) confirm a striking pattern, in line with expectations, if the land use trajectory already described of a forest’s path to pasture were played out over and over on one plot of land after another.

While 60 percent of the sample reported deforesting every second year, and an additional 25 percent reported deforesting every third year, patterns revealed by data analysis often deviated from reported frequencies. Deforestation activity was less prevalent in 1996, when about a third of the sample cut down some forest and nearly a quarter felled secondary forest fallow, compared with 1994, when 60 percent of the sample deforested and nearly 70 percent razed secondary forest. Thus, the spike in deforestation rates in the Amazon in 1994 and 1995, documented in Lele et al. 2000 and Cattaneo 2001b, also emerged in this household sample. The mean area felled for all farmers dropped from 2.5 hectares in 1994 to 1.5 hectares in 1996 for the forest, and from 3 hectares to 1 hectare in the same period for secondary forest regrowth. Among those who deforested, however, the mean area felled held steady at between 4.3 and 4.7 hectares in both years for both forest and fallow, although with substantial variation across households (Table 2.2). Over the entire period since their arrival, 1996 owners deforested on average 3.1 hectares per year,

²⁰Despite the ability to cross-check area reported in several sections of the survey, there is a possible difference across farmers in identification of particular land uses, such as the line between pasture degraded (perhaps to the point of little grazing) and secondary forest fallow regrowth.

Figure 2.3 Land uses upon arrival, in 1993/94, and in 1995/96

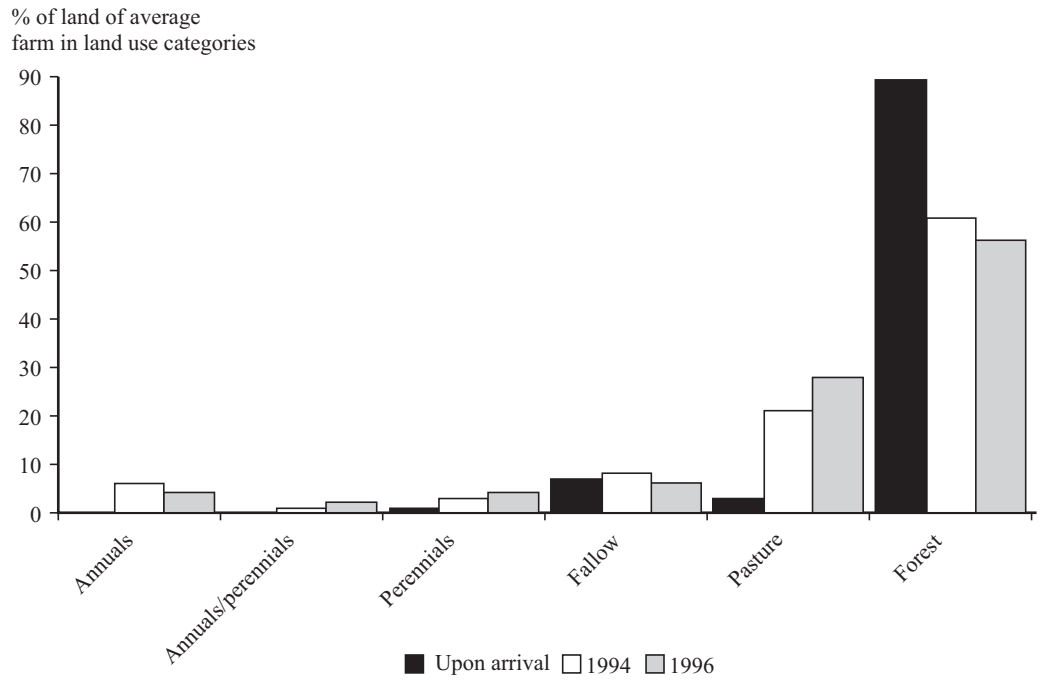
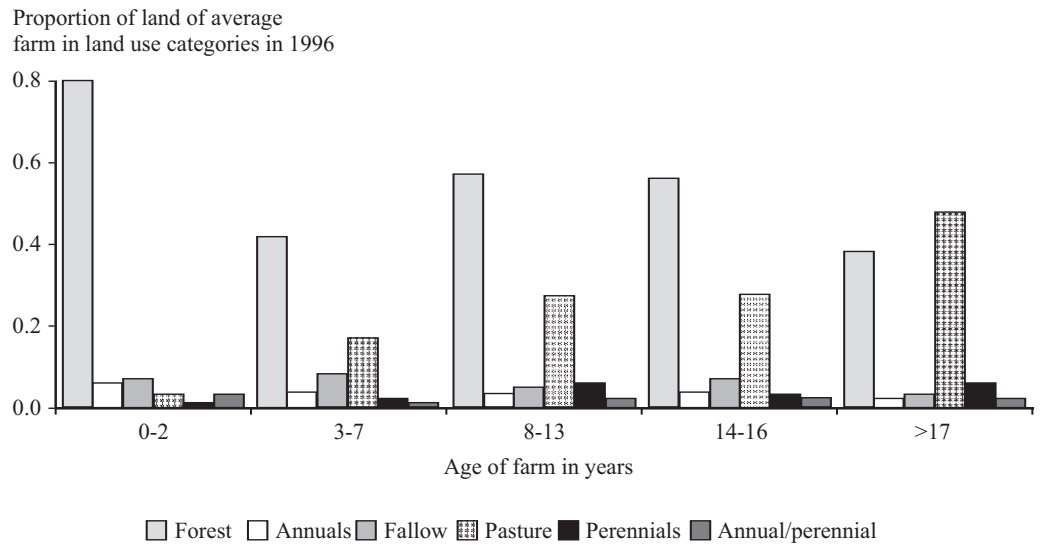


Figure 2.4 Land uses by farm “vintage”



Notes: “Vintage” indicates the number of years the farm has been in existence.

Table 2.2 Mean area felled in 1994 and 1996, primary and secondary forest

Area felled	Mean (hectares)	Standard deviation (hectares)	Minimum (hectares)	Maximum (hectares)	N
1994					
Forest	4.4	3.3	.50	20.6	80
Fallow	4.7	4.2	.50	29.0	75
1996					
Forest	4.3	3.0	.75	16.0	78
Fallow	4.4	6.9	.25	45.7	55

Sources: IFPRI/Embrapa/ASB field data.

but lots were deforested at an average rate of 2.5 hectares per year since their initial settlement. Lots opened more recently, but not with more recent owner turnover, had significantly higher average annual deforestation rates.

Older vintage farms with high proportions of forest remaining present examples seemingly counter to the playing out of the stylized land use trajectory over time and thus deserve special scrutiny. Of farms opened to settlement prior to 1985, 15 percent had less than a quarter of their land still in forest, 24 percent had between a quarter and a half, 40 percent had from a half to three-quarters, and 22 percent had more than three-quarters. These categories of farms were analyzed for significant differences in their allocation of land to uses other than forest. The least forested older vintage farms had proportionally more fallow land than the most forested farms, a finding that jibes with the idea that nutrients made available by cutting and burning secondary forest fallow biomass can partially substitute for those garnered from forest once the forest stock has been depleted. Farms with proportionately more pasture also tended to have more land in pure perennial stands and less land intercropped in annuals and perennials. For these farms,

the pasture-to-perennial land ratio stood at between 3 and 4 to 1: for every plot of land deforested that traveled along the trajectory toward perennials, three or four of the same size went toward pasture. Analysis of the 1996 sample as a whole revealed pasture-to-perennial land ratios of 4 or 5 to 1.

For the older vintage farms with the most forest, however, this pasture-to-perennial land ratio was closer to 1 to 1, and significantly higher proportions of land were allocated to perennials intercropped with annuals than in the two groups with the most pasture. This high-forest, older vintage group was more likely to be found in the North of Brazil, and although it might seem like a success story in environmental terms, there was an income trade-off: this group had fewer consumer goods, less secure tenure, and was located on poorer soils than the two groups with the most pasture (and least forest).

Indeed, cross-sectional field data show that project farmers, on average, generate output of higher value from cleared than from forest area in a given year, a relative profitability story echoing findings seen for the land use trajectories above. Using field data on land uses adopted by an average farm household and secondary prices for 1994 as a basis, the value of total output

(VTO) for the 1993/94 season is estimated to have averaged R\$3,448,²¹ which is a reasonable proxy for net returns given the low level of cost outlays in production. About 46 percent of this was derived from cattle-based activities (milk plus the value of growth in animals younger than five years), 45 percent from annual cropping, and less than 10 percent on average from extractive activities. Analysis for 1996 output yielded similar results. For the average family size in the sample (five members), R\$690 per capita ranks above the World Bank estimated poverty line for 1995 as well as the Brazilian minimum wage. This indicates that, for the most part, roughly 15 to 25 years after the establishment of a project, farmers have little incentive to depart from farming to enter the off-farm labor force (Faminow et al. 1999).

Land Quality and Production Activities

The farm surveys provide evidence of production patterns for the area and details about prevalent cropping patterns, management techniques, and, for livestock systems, herd demographics that are used in the bioeconomic model (see Chapter 4). These are described in this section, after a brief summary of the heterogeneity of agricultural potential in the sample, taken from survey information plus secondary data drawn from soil maps of the area.

Eighty-three percent of farms have access to water on their lots year-round, less important for crop production in this area of rainfed agriculture than for cattle, since animals must be sustained during the dry season. Soil quality is patchy in the projects; soil and topographical analyses of the projects identify areas with one or more of the following impediments to agriculture: low soil fertility, waterlogging, rocky soils, or steep topography.

Researchers, in conjunction with soil scientists, created four soil categories (and subcategories within them) based on combinations of these impediments and associated with sample lots.²² The scale of the Pedro Peixoto soil map is fine enough to discern soil types present on specific lots, but the resolution of the analyses themselves means boundaries for soil types might not be exactly depicted on the map, and patches of other types of soils may be found within areas characterized as homogeneous. For Theobroma, soil areas are mapped out at a coarser scale, and rough proportions of types of soil within that area described. Results of soil analyses performed to ground-truth the maps and provide input for the bioeconomic model appear in Chapter 4. For 35 percent of farms, more than one type of land quality is identified using boundaries as drawn on the Pedro Peixoto and Theobroma maps, but only the class that predominated on the farm according to the Pedro Peixoto map or

²¹All currency in this section is expressed in December 1996 reals. Note that the estimate assumes that the same local prices (derived from the price series for markets near the Acre study area, on average somewhat higher than prices in markets around Theobroma, Rondônia) were faced by all sample farmers, so differences in VTO across farms result solely from differences in production.

²²Rather than use classifications of soil type and other characteristics to establish a hierarchy per se of soil quality, the ranking used here classifies land, based on the primary constraints to agricultural production among its characteristics, constraints that vary depending upon the intended land use and might be overcome through management or technology. Information for this classification came from analyses done in the 1970s and 1980s. For Pedro Peixoto, this consisted of results of a spatially detailed soil analysis done in 1978 and a map demonstrating soil aptitude generated from this. For Theobroma, soils data came from an analysis by Embrapa in the mid-1980s, with much lower spatial resolution.

predominated in the area in which the farm fell, according to the Theobroma map, is used for the purposes of this report. The sample percentage associated with each soil type appears in parentheses after its description.

Land quality 1. These are soils characterized by at most a single and not severe limitation. Class 1a identifies the best soils in terms of fertility with no physical limitations identified (5 percent). Class 1b has a primary but not severe constraint of soil fertility (22 percent). Class 1c has no significant fertility constraint but is constrained by (nonsevere) slope (3 percent).

Land quality 2. These soils pose at least two limitations for agriculture. Class 2a is characterized by rockiness and fertility problems (14 percent). Class 2b has, in addition to these two problems, a limitation due to slope (27 percent).

Land quality 3. These soils exhibit poor drainage and therefore suffer from waterlogging during the rainy season (4 percent).

Land quality 4. This category is used to identify land with a severe slope, sometimes in combination with rockiness and limited soil fertility (24 percent).

Of farms surveyed in 1996, the most prevalent land uses were forest (98 percent of farms still had land in forest) and pasture (92 percent had land in pasture averaging 24 hectares). Slightly fewer (81 percent) had land in annuals (averaging 4.4 hectares), with 75 percent of the sample

producing corn, 67 percent rice, 61 percent manioc, and 55 percent beans. Fewer (67 percent) had land in perennials (averaging 4.7 hectares, including about 14 percent of the sample who had agroforestry systems), with coffee grown by about half the sample and bananas planted by a third. Nearly two-thirds of sample farms (64 percent) had land in secondary forest fallow (averaging 6 hectares), and 38 percent had land intercropped in both annuals and perennials (on an average of 3.1 hectares).

Table 2.3 shows average yields and distribution for the primary annual crops and the primary perennial—coffee—based on the 1994 sample, in line with the state figures reported above (the yield for manioc was not possible to calculate because the intermittent harvesting made it difficult for the interviewees to recall). Average yields calculated did not vary much between 1994 and 1996; 1994 figures are reported here because the survey instrument in 1996 did not capture output figures as cleanly.²³ The upper 20 percent of producers (80th percentile column in Table 2.3) managed to obtain yields close to those of research stations, but field data confirmed low use of external inputs for annual crops. Only one or two producers for each crop applied fertilizer of any kind; close to 15 percent of producers applied insecticide on rice and beans (5 percent for corn), and the same percentage of producers applied herbicide on beans (5 percent for rice and corn). Only a handful of producers used nonfamily labor in annual production. For coffee, 14 percent of producers reported using some kind of fertilizer (chemical or organic), 8 percent used insecticides, 14 percent used

²³The flaw in design, which stemmed from an attempt to distinguish between output, off-take, and storage inventory differences, occurred in the field but did not emerge as a factor in field tests and in-field data analyses. In most cases, information in the surveys does allow for this distinction to be made, but that information is not cleanly coded and requires a case-by-case examination of the hard document, deemed unnecessary for the purposes here.

Table 2.3 Crop yields, 1994

Crop	Mean yield (kg/hectare)	Median yield (kg/hectare)	Standard deviation (kg/hectare)	Percentile		N
				20	80	
Rice	1,194	1,200	619	604	1,736	115
Corn	1,110	960	862	372	1,983	99
Beans	366	248	366	96	600	99
Coffee	501	283	533	29	992	29

Sources: IFPRI/Embrapa/ASB field data.

herbicides, and 4 percent reported bringing in labor from off farm. Many coffee farmers (44 percent) had only trees in the establishment phase. Of banana farmers, only one reported using any external inputs, and 64 percent were past the establishment phase.

The yields also reflect a high incidence of intercropping. Figures for the 1996 sample are reported here, since the 1996 survey was more detailed, picking up spatial distributions of land use (interviews and aggregate data for annuals suggested that annual intercropping patterns did not change in the two-year period spanned by the survey). In 1996, 21 percent of the farmers cropped rice alone and 18 percent cropped corn alone. An additional 11 percent of farmers of each used a relay cropping system in which one *or* the other crop was succeeded by a bean crop toward the end of the rainy season. More prevalent was the case where rice and corn were intercropped with each other (and sometimes with a perennial as well), and followed by a bean crop. Manioc was planted alone by 52 percent of the farmers who produced it (usually in the second or third year after the burn of primary forest, or first or second year after the secondary forest burn).

About a third of farmers of rice, bean, and corn sold some of their output, com-

pared with only 6 percent of manioc producers. For those who grew coffee trees, 65 percent reported sales of their output (an additional 9.5 percent were storing their coffee, most reporting that they expected to sell it eventually, and 8 percent reported that the coffee was for home consumption only). Of banana farmers with trees bearing fruit, 27 percent sold some of their produce.

Close to 20 percent of the 1996 sample reported owning no cattle, although some without cattle did have pasture. In fact, about 25 percent of farms owned cattle that stayed on someone else's property and 25 percent had someone else's cattle on their property. This was one type of sharing arrangement found in the area: neighbors lend the use of land in exchange for the product from that land, or for the use of other land (for example, they trade the use of annual land for pasture land), or for labor days. Sometimes these arrangements span agricultural years. The survey found evidence of land sharing in 21 percent of sample households. Of those with cattle, herd size averaged 23 animal units, or 32 head. On average, cows accounted for 40 percent of the herd, calves about 28 percent, and steers or heifers under three years an additional 24 percent. The stocking rate averaged 1.1 animal units per hectare of pasture, ranging from 0.5 to 2.7 animal units per

hectare.²⁴ Close to 40 percent sold cattle and 30 percent purchased cattle. Counting cattle sales and purchases as well as births and deaths, there was a net herd increase of 1,317 head among the 81 percent of the sample owning cattle, an average increase of 7 head. Yet, of these farmers, 13 percent had shrinking herd size (usually just 1 or 2 fewer head), while 11 percent maintained their herd size over the year. The vast majority of cattle producers—three-quarters—increased their herd during the year, by an average of 10.5 head, but the distribution was skewed by the presence of medium-scale farmers in the sample. Fully one-third of those increasing their herds did so by 3 head or fewer, the median response was 7 head, and the top one-fifth increased their herds by 17 head. About 82 percent of 1996 cattle farmers had cows producing milk; almost a third of milk producers sold their output, but these were disproportionately in Theobroma. Difficulties in marketing milk were reported in Acre primarily because the road infrastructure was poor (J. Valentim, personal communication, 2000). Those who did sell milk faced a quota (price drop-off) that reflected this bottleneck (an issue taken up again in Chapter 4 on the bioeconomic model).²⁵ The number of cows giving milk stayed roughly the same from rainy to dry seasons—with a mean of about 6 cows per farm, but daily production dropped from a mean of about 4 liters in the rainy season to 3 liters in the dry among dairy farmers.

Technology for cattle production systems varied considerably as well (Vosti et al. 2001a). In the 1996 sample, 84 percent

burned their pasture annually to clear it of weeds. Nearly 60 percent reported planting what they termed *brachiarinha* or *brizantão*—the grass variety *Brachiaria brizantha* cv. Marandu (although this is likely an underestimate, since an additional 24 percent reported having “mixed” pastures, at least some of which, and perhaps all, include this variety). This variety, which first became commercially available in 1983, was widely adopted because of its ability to establish itself quickly and produce a substantial amount of forage (J. Valentim, personal communication). Since the survey, starting in 1998, reports of the death of this pasture in both Acre and Rondônia have expanded, causing total degradation of pasture for some. This loss is hypothesized to stem from a combination of overgrazing and poorly drained soils, resulting in a build-up of previously benign pests to pathogenic levels in the soils (J. Valentim, personal communication; Valentim et al. 2000). Only 4 percent of farmers planted *Brachiaria humidicola*, which is currently not experiencing a problem, and an additional 4 percent planted *pueraria* (tropical kudzu), mixed with other grasses. The kudzu fixes nitrogen, provides forage for cattle, and suppresses weeds for farmers who are reformulating pastures suffering from pests (J. Valentim, personal communication).

All but 17 percent of cattle farmers had at least some fencing on their pasture land (most had built the fence since their arrival), and 45 percent had a small dam or reservoir to trap water for the herd. Only 4.5 percent of the cattle farmers grew

²⁴This is calculated only for households with cattle but with no sharing arrangement (as the herd composition of cattle on other lots was not surveyed).

²⁵Processing capacity was gearing up in the state at the time of the survey, however, and this was publicized among smallholders, so widespread milk production in Acre may have been linked to anticipation of expanded opportunities. By 1999, however, the excess processing capacity persisted (J. Valentim, personal communication, 2000).

forage to feed to cattle in the dry season. Forty-six percent separated newborn calves and their mothers from the rest of the herd. About 75 percent of cattle farmers used mineral salts. Vaccination prevalence rates ranged from 25 to 75 percent of cattle farmers, depending on the disease. A second survey of a subset of farms revealed that vaccination patterns did not usually follow prescribed practices.²⁶ One important finding of this more detailed (but smaller) survey was that herd quality was amazingly high regardless of area and level of management (although it was felt that herd size might be at some threshold where lack of appropriate management might start to have more serious consequences for productivity).

In 1996, 67 percent of farmers reported extracting some product from the forest. Of these, 62 percent extracted Brazil nuts, just over 50 percent extracted some wood, 38 percent hunted, and 14 percent fished. Half of those extracting Brazil nuts reported sales (this includes those reporting that they planned to sell but had not yet collected); the others stated extraction was for home consumption (amounts unknown). A quarter of those extracting wood sold some off-farm (the main on-farm use reported was for fencing).

About 40 percent of 1996 households hired out some labor during the agricultural year, primarily for deforestation activities but also for pasture maintenance. Roughly 50 percent hired in labor the last time they deforested (and just under 20 percent traded labor days); 23 percent hired in the last time they cut secondary forest (9 percent traded days).

Lot and Ownership History

The majority of farms in the sample, 69 percent, were opened for agricultural use for the first time between 1980 and 1982 (nearly 35 percent in 1980 and about half that many in each of the two subsequent years). By 1996, farmers had practiced agriculture on these lots for 14 to 16 years. About 8 percent of the sample lots have supported agriculture even longer, having been opened by settlers before this major wave began (sometimes by squatters whose arrival preceded the official INCRA opening and sometimes by rubber tappers who had lived previously in the area as extractivists on a rubber plantation). The sample reflects a small but steady flow of new lot openings each year after the wave of openings in the early 1980s until the survey year. Some areas of public forest reserves within the project still exist, into which invaders encroach to open up new lots. The vast majority of the land, however, is allocated by INCRA to smallholder families, who retain use rights to the land (including the forest, with some proscriptions on deforestation and forest extraction, as already described). They initially obtain a document recognizing their presence, which over the course of approximately five years evolves into a right to a definitive title to the land.²⁷ Only after holding the definitive title for several additional years do lots leave the public INCRA system, at which time smallholders are technically allowed to sell their lots. In reality, however, sales and exchanges of lots take place at all points in the process, with farm tenure evolving as a mix of public and private legal systems, with formal

²⁶About 40 randomly selected cattle farmers in these projects (plus 5 from an even older project in Rondônia, Ouro Preto do Oeste) were interviewed in more detail about cattle inventory and management practices by a local veterinarian and pasture expert, who also made independent assessments of herds and pastures.

²⁷Those who encroach upon forest reserve land do so illegally, yet it is common practice for INCRA to incorporate these lots into its system every few years, with squatters earning a document that can evolve into a definitive title. There are some bureaucratic costs to the gaining of a new title, and backlogs at INCRA mean that an actual registered title may lag behind the document.

systems rarely keeping up with common practice.

Lots distributed to migrants got progressively smaller as time passed, ranging from 100 hectares near the initial opening of the settlement project, to sometimes less than 25 hectares at the time of the final survey round. Despite the legal prohibition against land transactions for a period of roughly 10 years after initial settlement (part of the policy intended to “fix” migrants to the land), land transfers occurred, and the size of an operational holding sometimes shifted with them. By 1996, 80 percent of farmers still owned one lot, 15 percent had two lots, and the remaining 5 percent had more than two. A strict lot tally can overlook transfers of portions of lots allocated by the land reform agency. In the two years covered by the survey, 13 percent of panel farms were involved in transfer of some land area, roughly split between buyers (averaging 68 hectares) and sellers (averaging 56 hectares). Six farms were sold out of the sample entirely, to larger ranching enterprises. Over the longer term (since farmers’ arrival on the lot), however, 11 percent of 1996 farmers had bought land (on average 69 hectares), compared with 2 percent of farmers selling land (a mean of 19 hectares).

The sample also showed substantial evidence of owner turnover. Just under a third of sample farms still had their original owners at the time of the 1996 survey. Of the 1996 sample, 22 percent of owners had arrived within the last three years. This was not solely because the sample was expanded in 1996 to include invaded areas: the 140 lots surveyed in both years also tell a story of ownership change—11 percent had new owners. In 4 percent of the cases, ownership changed within the same family (approximately 9 percent of households re-

ported joint management among multiple heads of household, usually from the same extended family). Farms that changed ownership did so only rarely via inheritance (2 percent of the sample). Ownership changed primarily via purchase, trade, or some combination of the two, with 20 percent of farmers having registered the transfer with a notary. This created a paper trail that was sometimes the only thread tracing the path from old owner to new, with the INCRA title remaining in the name of the original owner. Despite some anecdotal accounts of insecure tenure leading to the ousting of an owner, this was described as rare among smallholders and did not occur within the sample—nor did outright conflicts with large landowners, who feared appropriation of their lands under a revised land reform law. (Alston, Libecap, and Schneider 1995 say that the evolution of the law and incentives policy may have promoted social conflict inadvertently.) Still, interviewees at the delicate stage prior to initial INCRA recognition of their settlement in forest reserves—the situation for less than 5 percent of sample lots—did evince some qualitative signs of insecurity, notably in their wariness about the purpose of the survey.

Tenure may have played a more important role in guaranteeing access to formal credit than security of land rights *per se*. Only landholders with some form of documentation (private or public) recognizing their presence on the land could become eligible for government-sponsored rural credit plans (although, more recently, in some projects in Acre this restriction has been lifted) (J. Valentim, personal communication).²⁸ That said, more secure tenure (the case for 58 percent of the sample) can open doors to more varied lines of formal credit from different sources than would a simple proof-of-presence document

²⁸ Agricultural extension agents also play an important role in identifying claims to land. A letter from an extension agent, for example, attesting to stewardship of land (improvements), can sometimes be sufficient proof of ownership to secure formal credit.

(possessed by 23 percent of sample households). Beyond credit access, tenure may confer additional value to the land asset (Samuel Oliveira, personal communication 1997).

Absentee landlordism (whereby the farm is managed by a hired caretaker who lives on and works the farm for the owner, receiving a fixed portion of the resulting production or revenue from its sale in compensation) is sometimes anecdotally cited as an indicator of land speculation in project areas. Although present in the projects, it was by no means prevalent, accounting for only 6 percent of farms sampled (with evidence that three owners from the panel had become absentee landlords in the two years separating the surveys).²⁹

Household Characteristics

This subsection briefly describes household characteristics in 1996, at the time of the survey. The average age of the head of household was 46 years, with roughly 25 percent of household heads over 55. Forty-seven percent of household heads had the ability to read and write on at least a rudimentary level, although this measure may fall short of a reliable yardstick to measure ability to easily integrate information on markets or technologies. In each year surveyed, households averaged five to six members. For farms visited in both years, about 600 individuals were present both times, while approximately the same number of people, 100, entered the sample via in-migration and birth as left it. Dependents comprised nearly 45 percent of the household, on average, but the ratio of children to working age adults approached 1 to 1 (0.86). Of those of working age, on average, 59 percent were males.

Of a list of 11 household durable goods likely to be found in the projects, 1996 sample households had, on average, 4–5 of them, but nearly 25 percent had 2 or fewer. The most prevalent items were a radio (67 percent), a bicycle (63 percent), and a chainsaw (57 percent). There were some signs of relative affluence in the sample: 23 percent reported having an urban property, 15 percent reported having a television, and 11 percent reported having a car.

When asked about savings mechanisms, only 3 percent of the sample reported having bank accounts, while many mentioned cattle as their source of liquidity. Roughly 21 percent said that they turned to informal credit in times of need (from neighbors, family, or marketing middlemen). About 24 percent of the sample was paying off formal credit loans at the time of the survey. Nearly 37 percent of the sample received some kind of pension on a regular basis, and an additional 5 percent received remittances from family members.

Migration History

Schneider (1992) and Ozorio de Almeida and Campari (1995) note the importance of migration history to agricultural practices in newly settled areas. Agricultural extensionists stressed the importance of commonality of origin for social interaction, including producers associations, early in the life of a settlement project. The majority of migrants in the 1996 sample came from the more developed southern region of Brazil, a total of 57 percent from the South and Southeast combined. Some had been displaced by agricultural modernization and hydroelectric projects there (Ozorio de Almeida and Campari 1995). Nearly a third of the settlers, however, grew up in the

²⁹The terms of the arrangement vary considerably. Notably, the level of owner involvement varies, and with it, the role of primary land use decisionmaker—a matter of interest to the study and the subject of the survey—can shift to the caretaker.

north of Brazil—the Amazon. Virtually all settlers were familiar with rural life before they came to the project, and just over half (51 percent) reported familiarity with urban life as well. Leña (1991) points to the potential importance of settlers who perpetually migrate from one frontier area to the next, moving on as development occurs. In this sample, more than 40 percent of the sample passed through two or more states from their state of origin before arriving in the colonization project. Before coming to the project, only 64 percent of 1996 landowners lived on a farm to which they had some sort of tenure claim. Of the others, the biggest group—12 percent of the sample—lived with a relative already in the project. Some migrants, about 15 percent of the sample, had moved from one lot to another within the project before obtaining one of their own (one settler had moved four times in the project).

In the sample, the first migrant arrived in 1953—before there was a project—and the last migrants, 15 of them, arrived in 1996, the year of the survey. The bulk of lot openings occurred between 1980 and 1982; after that, the number of 1996 owners who arrived in any given year remained remarkably steady, marking a second generation of settlers for most farms. There is evidence that second-generation settlers were better off than their predecessors when they first arrived: they had sufficient financial resources to support the family on average for just over five months, significantly longer than the three-and-a-half months of the first-generation migrants.³⁰ Only 3 percent of households reported having a separate steady source of income—from pensions and remittances—that supported them upon their arrival. Households newly arrived to the lot had, on average, three adults and

about two children (there was no significant difference between “generations” of settlers).

Off-Farm Characteristics

The furthest reaches of the projects lie about 125 kilometers from markets, with some areas virtually inaccessible when roads and bridges wash out during the rainy season. Market access, however, also depends on the mode of transport available to the farmer and road quality, as well as the way the market in question works (middlemen may, for example, come to the farmer). Farmers in the projects spent about three hours to get to the nearest market town in the dry season (80 percent of the sample). In the wet season, the time to get to market doubled, on average, but again the variation among farms was substantial (with 5 percent of the sample experiencing five-fold increases)—indicating differences in the susceptibility of project road systems to seasonal damage from rains.

Seventeen percent of households reported that they lived on roads where no vehicles passed in the dry season. This figure jumped to approximately 40 percent in the rainy season. When vehicles did pass, they were usually of only one type, often a bus or a four-wheel drive vehicle. Nearly 10 percent of the sample, however, had three or four types of vehicles passing (often including a milk truck). Roughly half the sample reported that some vehicle passed on their road at least once a day in the dry season, but only 35 percent of the sample saw one vehicle a day or more in the rainy season.

At the neighborhood level, identified by the road, or *linha*, along which a lot fell, local associations and churches regularly

³⁰For a similar finding in Ouro Preto do Oeste in the state of Rondônia, see Leña 1991.

organize projects related to production, marketing, or education and members participate in them. Work parties were often built up around church and denominational groups (Sydenstricker 1998). Nearly all farms (90 percent) were located on roads where at least one farmers' association existed. Every road had a Catholic church; 75 percent of farms had easy access to an evangelical church. Just under a third of sample farms had access along their road to a local labor union. Population density varied dramatically from one *linha* to another, ranging from 3 to 60 people per square kilometer, with a mean of 9 across sample households. Higher population densities were significantly and negatively correlated with the proportion of sample farm area left in forest (Pearson correlation -3.44 , $N = 50$ *linhas*).

Principal Findings

On farms in the sample, the area in pasture is going up, while the area in forest is going down; swidden long-cycle fallow is not practiced. Perennial cropping appears to be a land use with the potential to slow deforestation, but more area in perennial crops may not guarantee more area in forest. Rather, there appears to be a finely balanced investment in terms of land in perennials and pasture. Evidence here suggests that, in the years leading up to 1996 at least, perennial cropping as a land use did not lead to a better or even equal standard-of-living than did the more prevalent pasture-dominant route: indeed the standard-of-living was significantly lower.

The general trend in land use—conversion from forest to pasture—held despite the fact that substantial variation in

production technologies was evident, particularly in the case of pasture. The survey showed some evidence of more intensive use of land via intercropping and pasture management, but purchased inputs remained the exception.

Deforestation rates varied and seem to have accelerated as more time has passed since the lots were initially opened, with more than a few farms crossing over the 50 percent-of-farm-in-forest barrier decreed by law. This finding is in keeping with the idea that pressures to deforest are greater in an environment with higher populations and more markets than in one where farmers must rely on the lot alone (and household labor alone) for subsistence. Indications are, however, that the size of land cleared (of secondary or selectively logged forest) stayed relatively constant, and it was the timing of the clearing that varied, providing a potential entry point for policies seeking to put the brakes on deforestation.

Some in the sample, moreover, were doing quite well—buying new lots and consumer durables, reaching near research-station yields, and commercializing their output—while others have fewer signs of wealth, lower yields, and more limited access to and participation in labor and output markets. This suggests an important bimodality in the sample in terms of those who are succeeding in capitalizing at the forest margins, and those who are not.

This descriptive analysis highlights trends regarding land use and raises both temporal issues regarding land use trajectories and spatial ones regarding who makes decisions for what land at what time. These issues are explored via multivariate analysis in Chapter 3 and the bioeconomic model in Chapter 4.

CHAPTER 3

Multivariate Analysis

This chapter sets out a general theoretical model of the determinants of land use based on profit maximization under the biophysical and economic constraints prevalent in the study site. The biophysical constraints are embodied in the land use trajectory and land use qualities described in the previous chapter, given virtually nonexistent use of fertilizer within the sample. The economic constraints are measured in terms of farmer characteristics and endowments regarding primary inputs of land, labor—manpower and human capital—and asset capital, given imperfect markets in these.³¹ These constraints bind at different levels for different households, determined by the degree of access to existing markets and possibilities for trading among neighbors via existing social networks facilitated by rural institutions. Land use choice is dynamic in nature, given that stocks of both land quality and factors carry across from one period to another and that decisions are made with expected profits from a future stream of benefits from land uses in mind.

The chapter first lays out a general theoretical model, briefly setting the model in the context of existing literature on deforestation, and derives an equation to be estimated given available data. It then outlines hypotheses regarding the effects of market access and constraints on land use choice, presents a subset of the results of these tests obtained from multiple regression analysis, and discusses implications of those results, including limitations of the model, for policy and future research. A complete set of descriptive statistics for all variables used in this analysis and a full set of regression results are presented in Appendix A, Tables A.1 and A.2, respectively.

The Model

A General Model for Production

In broad terms, the same general model of household production underlies analysis in this chapter and in Chapter 4 (on the farm-level bioeconomic model, the structure of which is

³¹The biophysical constraints could easily be incorporated into the economic ones under land quality, much as manpower and human capital describe labor quality. They are separated here and in results to isolate their effect on land use patterns over and above the most often used proxy for land endowment in studies at the household level—farm size. Studies at the regional level increasingly incorporate more sophisticated measures of soil quality, topography, and other landscape features (see, for example, Chomitz and Gray 1996; Chomitz and Thomas 2000; Nelson and Hellerstein 1997).

described in the text and algebraically in Appendix B). This analysis makes different simplifying assumptions to explore different aspects of land use decisionmaking via a different tool, one that exploits the heterogeneity of endowments and degree of market access in the sample to pinpoint their importance for observed land use decisions. The farmer's profit (Π) maximization problem (subject to production technology and resource constraints) for a given period is defined as³²

$$\begin{aligned} \max P &= (P \bullet Q - w \bullet R) \\ Q \\ \text{s.t. } Q &= f(R) \\ R &\leq R \end{aligned}$$

where P is a vector of exogenous output prices at farmgate, Q is a vector of products potentially produced using farm resources, w is a vector of exogenous input prices (or endogenous shadow prices if input constraints bind), and R is a vector of inputs used in production activities, R being constraints on those inputs (in the case of finite endowments), and $f(R)$ representing the multiple input–multiple output production function for Q . For the purposes of the model here, Q includes agricultural and extractive activities, as well as labor sold off-farm, and P as well as exogenous w are each a function of factors, including price signals formulated at national and regional levels and household access to markets. Either can be influenced by transportation cost to markets and available social networks (to facilitate either links with markets or to provide trading partners for a more locally formed price). In a one-period model, land and its characteristics are fixed factors.

In the dynamic problem, the above expression is maximized over time from the present moment stretching out forever (or a salvage value equivalent to maximum future profit streams can be included after maximization over a finite period). This modification adds considerable complexity. Price vectors over the time horizon (that is, a vector of time paths for prices) are in terms of expectations; production functions must (1) be defined more explicitly in terms of timing of inputs and outputs; (2) include, for land, costs of conversion from one land use to another, and (3) themselves be subject to expected changes in the future, if the farmer predicts agricultural improvements. Price and production expectations incorporate, moreover, expected weather patterns and policy contexts. Constraints on inputs may shift each period, depending on the time path of decisions up to that point (a state equation for R); some inputs, such as soil type, remain fixed throughout the time horizon and have no explicit input price.³³ Changes in land quality due to biophysical processes combined with management can be incorporated in the time-sensitive production function, or within the time path for the input vector R , with the latter preferred under the idea that all farmers face identical production functions, but with different resource constraints. Changes in human capital would then also fall within the time path for the vector R (later referred to as “time sensitivity” of that vector).

In this constrained production model, farmers choose combinations of activities that maximize profits. The profit maximizing time-sensitive vector of output Q^* ,³⁴ implies an optimal set of inputs R^* for each

³²This derivation follows Greene 1999, Chapter 15, pp. 693–96. Letters representing vectors appear in bold typeface.

³³This could change if the model more realistically took into account spatial allocation of production activities—the choice of matching activity to soil type; findings from this report could indicate whether that level of detail would be warranted.

³⁴Because of the constraints on key input levels, the possibility of infinite profits from infinite output does not arise, apart from the question of returns to scale of the production function.

time period via the (known) production function, including an optimal set of land uses per period (I^*). Derived demand for R^* , including I^* , will be the solution to minimizing costs subject to the production and other constraints, for the output level Q^* . It will thus depend on the vector of input prices, and fixed and constrained factors, and Q^* (itself a function of the full price vector for inputs, outputs, and fixed and constrained factors).

To identify factors influencing land allocation, then, one could regress observed land allocation on the full price vector and fixed factors and constraints. Ideally, derived demand for land would be part of a system of equations for all R since inputs are jointly determined. Ideally, estimation of production would be part of a system that incorporated consumption decisions, since limits on available inputs due to imperfect markets imply that households' consumption and production decisions are jointly determined. Because of inadequate data to estimate a full system, the focus here falls on production and land use (Walker, Moran, and Anselin 2000 also focus only on production, even though it depends explicitly on family labor and wealth; Jones et al. 1995 do likewise in the face of evidence for nonseparability similar to Pfaff 1997 and Chomitz and Thomas 2000, for example). This limitation adds a caveat to interpretation of regression results, but biasing results by introducing poorly specified consumption or derived demand to the estimation would also not be satisfactory, with results probably more difficult to interpret. Before proceeding to the derivation of land allocation equations, how the theoretical context fits in with the existing literature is briefly examined.

Other Models for Determinants of Land Use (Deforestation)

Some deforestation regression analyses lack a specific theoretical underpinning; Andersen (1996), for example, notes the

lack of consensus on a theory of deforestation and estimates an empirical model at county level that includes factors that some point to as important for deforestation. The model described at the beginning of this section, although not yet at the level of empirical estimation, resembles that proposed by Pfaff (1997) for the plot level (from which he derives a county-level deforestation model and tests using data at that level), but it differs in several important respects. Pfaff's model is for a single period, with optimal land use determined by highest immediate returns to plots of land of fixed size—maximum profits from use of that land. It thus does not explicitly incorporate expectations (except future price expectations based on current ones) or an optimal path of land use over time. Based on sample pooling from two points in time a decade apart, it cannot test for the importance of path dependency in land uses (such as the role of secondary forest fallow). Because of data constraints, it distinguishes only between forest and cleared land, not land allocated to particular land uses. Pfaff points to the benefits of having data that (1) allow plot level estimation, (2) incorporate dynamic elements touching on determinants of future returns such as property rights and include past land uses as determinants of present ones, and (3) distinguish between multiple land uses. Perhaps most important, however, Pfaff assumes that land use decisions are determined by exogenous market conditions at some level, with prices conditioned by farm location vis-à-vis markets and other institutional and policy factors, plus fixed characteristics of the land. Optimal land use by plot is thus determined entirely by factors exogenous to any land user—that is, not contingent on specific characteristics of households such as wealth and labor endowment. Indeed, land area analyzed in his model is not necessarily in the hands of any private owner.

This general assumption vis-à-vis markets is shared by Chomitz and Thomas (2000), who abstract away from plot level

to an area unit of observation made possible by integrating agricultural census and satellite and other spatially explicit data. They include a land use category of “productive but not utilized,” which allows more analysis of strict economic viability than would otherwise be the case. They assume random variation in land quality within the unit but have a good deal of detail about the average soil quality in that unit, its natural land cover, average precipitation, and position vis-à-vis economic centers (roads, cities). In their model, the proportion of land optimally converted to a specific use (their focus is on the proportion of area in agriculture broadly) within the unit reflects average costs (negatively related) and benefits (positively related). Yet the market itself is not in a stable equilibrium in the context of a dynamic frontier: observed land use proportions do not necessarily reflect optimal land use, but they are headed in that direction in a way that reflects not just potential profits but prior land conversion in the area and in some geographical band around it.

Both Jones et al. (1995) and Walker, Moran, and Anselin (2000) are closer to the model presented here in that they estimate equations at farm level and include household characteristics—such as wealth and human capital or family labor or both—alongside hired labor.³⁵ Walker, Moran, and Anselin (2000) estimate a “production

function” for pasture land, dependent on labor—hired and family—capital, and life-cycle variables, with endogeneity of wealth and hired labor important topics, suggesting nonseparability of production and consumption decisions, although this is not explicitly discussed. Jones et al. (1995) attempt a more comprehensive analysis, estimating (1) multiple (Cobb-Douglas) production functions; (2) determinants of revenue; (3) equations for time on lot, location, and degree of diversification in a system that incorporates burning strategies; and (4) annual forest clearance, stock of cleared land, and income shares derived from cropping and cattle activities. This last comes closest to touching on all elements of the proposed production model with limited data, but the dynamics are more backward-than forward-looking (that is, how past practices affect current profit maximization, as opposed to applying a forward-looking view of profit maximization). They find evidence for nonseparability of production and consumption decisions at least in staple crops (but do not attempt a joint estimation).

The Model for Estimation

The model estimated here, like all of the preceding, focuses on land use as a dependent variable. Like Jones et al. (1995) and Walker, Moran, and Anselin (2000), it focuses on privately held land. Its structure

³⁵Neither estimates the consumption side of the model. In the spirit of Singh, Squire, and Strauss (1986), such a system would involve a household utility maximization problem subject to a budget constraint resulting from production decisions and value of household endowment, subject to relevant household resource constraints. It would include elements of expectations similar to those proposed by Barrett (1999) in an exploration of the role of food price stochasticity and slash-and-burn agriculture (essentially the first production cycle of the production model discussed here, since it holds technology constant and incorporates farmers' expectations about product prices in the postharvest period). It would also include dynamic elements similar to those proposed by Pagiola and Holden (2001) (a two-period model incorporating a choice of extensifying and intensifying technologies).

allows testing for whether land use decisions hinge on the fact that heterogeneous farmers are incompletely integrated into markets (so farmer's choice of optimal land use is constrained by factor endowments). It estimates household land use via data at the level of the relevant decisionmaker. Unlike the other models described, this model distinguishes among several uses of cleared land, in addition to differentiating between forest and cleared land. Like the Jones et al. (1995) model, it incorporates measures of land quality and human capital such as migration history and length of time in the project (but has less detail on physical capital than is present there). Unlike the other models, it examines the role of changes in size of operational holding on land use decisions. It shares with Pfaff (1997) an aspect missing from the other farm-level models, namely inclusion of local institutions important for exogenous prices or quality of resource endowments. The theoretical model here shares with most of the discussions behind these other estimated models a need to explain observed land uses in a particular period of time within a dynamic process thought to have both backward- and forward-looking elements (backward looking because both biophysical and economic resource constraints in that period are contingent on land use history; forward looking because the profit maximization decision is inherently forward looking). It shares with Chomitz and Thomas (2000) the idea that land conversion itself has some (unobserved) adjustment cost, so that observed land uses may

not be optimal, and it employs observations on past land use to help home in on the adjustment process.³⁶ The role of expectations here is, as in the models above, not explicit, since data constraints do not allow for price to directly enter the model (but rather factors that shift the farm-gate price from a regional price all farmers potentially face). Still, the expectation process is assumed to be similar across farmers, with actual expectations varying in accordance with the off-farm conditions that determine farm-gate price, plus farm and household characteristics affecting production (already in the model).³⁷

Regressors. More specifically, because farmers in each of the two fairly limited geographic areas that comprise the sample observe *price signals* emerging from the same local and regional markets, input and output prices do not directly enter the model. A site dummy, discussed further on, picks up differences in relative prices across projects, along with a host of other factors. *Farm-gate prices* do vary across sample households, and although not observed, are shifted by factors that are observed. Likewise, resource constraints that make prices endogenous to households vary across households. Collectively, these two types of price-shifter variables, derived from the descriptive analysis presented above, are separated into two categories of *Z* variables. The first category replaces market prices for products (*P*) and inputs (*w*), and the second category fleshes out factors for which the farm household might have endogenous

³⁶As discussed below, isolating speed of adjustment over a shorter period comes at the cost of diluting direct tests in the model for importance of particular resource constraints in land use decisions.

³⁷The extent to which high discount rates for poor farmers and a highly uncertain environment actually shorten the time period for which farmers realistically form expectations, in which case models that maximize profits period-for-period more closely approximate a dynamic optimum, cannot be tested using this analytical tool, although the bioeconomic model (Chapter 4) could provide some bounding arguments in the form of profit differences between period-by-period and whole time horizon maximization under high discount rates but under certainty.

prices (resource constraints R) in the final estimation equation.

The Z variables related to resource constraints at the time when land uses to be explained are observed (time t) include several subcategories, namely land quality (Z^N); land status (Z^S), including farm size and existing land uses and investments; human capital (Z^H), including knowledge and labor availability; household assets (Z^A)—a proxy to capture relative differences in capital availability across farms; and land tenure (Z^{TN}), for its role, described in Chapter 2, in easing the capital constraint via greater access to credit. The Z variables related to exogenously determined farm-gate prices (again at time t) also comprise several subcategories, including market access or transportation costs (Z^{TR}), local community associations (Z^{COM}), and land tenure again (Z^{TN}), this time because, as described in Chapter 2, it may play a role in expectation of future prices.³⁸

The full set of Z vectors is thus

$$Z \ni (Z^N, Z^S, Z^H, Z^A, Z^{TN}, Z^{TR}, Z^{COM})$$

The equation estimated includes important time subscripts on some Z variables, namely those proxying for R. This includes all household factor endowment (resource constraint) variables that change over time as a result of land use decisions, namely farm-level land status (Z^S), household human capital (Z^H), household assets (Z^A), and household land tenure (Z^{TN}). For these Z variables, the time path from the farmer's initial arrival on the current operational holding (or $t - \Delta$, where Δ represents time since the farmer initially arrived on that op-

erational holding) until time t matters for land use decisions taken at time t . Information about that time path cannot be captured for the purposes of this estimation by R variables at time t because they are jointly determined with the land use decisions. Variables to track changes in the stock of land (size of operational holding, a component of Z^S , namely Z^S_Δ) available to the household between arrival and time t —due to purchases or sales of land and recent ownership changes—are also included.

The other Z variables (Z^{TR} , Z^{COM} , and Z^{TN} , affecting current and expected farm-gate prices) are taken as exogenous to the farm household decision and slow to change, so they are measured at the time of the survey for their status at time t .³⁹ To control for changes in meso-level circumstances since the lot was first settled that could affect the time path of land use decisions on the lot, the equation includes t_0 (the year the lot was initially settled) and $t - \Delta$ (the year the time t owner arrived on the lot). To control for variables that vary by project (including state and local policy environment, population density, and local market prices), a project-level dummy variable (Z^P) is included.

Finally, the equation includes additional regressors in keeping with the idea that unobserved processes beyond the already mentioned Z factors associated with cost (in time and resources) of land conversion from one use to another may hinder complete adjustment to (constrained) optimal land uses (l^*) in time t . For this purpose, a lagged set of dependent variables (a subset of Z^S) is included on the right-hand side of the final estimated equation. Their

³⁸Land tenure (via the processes described in Chapter 2) arguably contains endogenous as well as exogenous elements, but endogenous elements have largely to do with decisions taken by the farmer in conjunction with arrival on the current lot. How the decision to settle in the project in the first place affects subsequent land use, while important, lies outside the land use focus under study here.

³⁹As noted earlier, aside from decisions taken upon arrival, land tenure is largely exogenous to other decisions taken by the farmer, but at time t may affect expectations of future profits.

presence controls for differences in various conversion processes (for example, the irreversibility of the initial forest clearing decision or the difficulty in recuperating land in pasture for other uses) without specifying the conversion processes precisely. These factors are posited to prevent farmers from reaching optimal constrained land use in the time period desired, making this a partial adjustment model. An additional variable is added to capture how changes in ownership during the “adjustment period” might have affected this trajectory (a component of Z_t^{TN}). The presence of these variables as regressors, however, changes the interpretation of effects of resource constraint variables (at the time of the arrival of the time t owner) on land use allocation in time t , since those same constraints also affect lagged land use. Theoretically, then, there should be some multicollinearity in this subset of regressors. Significant results on initial resource constraint variables in this context pick up persistent effects of these variables on current land use, even controlling for lagged land use. Insofar as past resource constraints proxy for current (endogenous) ones, this does not present a serious problem, but the time since original arrival is sometimes long enough that, while these variables contain information about current resource constraints, their exact interpretation may be clouded.

Dependent Variables, Error Structure, and Estimation Technique. The form of the dependent variable is the proportion of the operational holding devoted to each land use at time t , following the approach of Pfaff (1997) and Chomitz and Thomas (2000). In Pfaff (1997), the proportion variable falls out of the aggregation process in moving from the plot-level model to a county-level estimation. Pfaff assumes heterogeneous plots within the county, with plot-level unobserved characteristics affecting the profit differential between clearing and not, beyond what is known from county-level observed characteristics alone. Plot decisions, and the estimation procedure,

hinge on these error terms (assumed to be logistically distributed) around observed county-level characteristics. In Chomitz and Thomas (2000), the proportion variable also stems from assumptions about heterogeneity within observable land units—explicitly in land quality—in conjunction with the idea that observed land uses are moving toward rather than holding at an equilibrium in the context of an expanding frontier. They assume a truncated normally distributed error structure. The censored dependent variable might then suggest a Tobit estimation, but they use an iterated quantile regression method for consistent estimation because census tract data or spatial patterns potentially important in their model could introduce inconstant variance (heteroscedasticity) to error terms.

In this report, a somewhat analogous aggregation problem is faced: plot-level characteristics at time t associated with particular land uses are unobserved but summarized at the level of the operational holding, and these affect the proportion of the farm allocated to each land use. The presence of more than two alternatives—thus more than one choice (since valuation comparisons of alternative land uses now involve finding the highest valued alternative through a series of pairwise comparisons)—complicates assumptions about error structure beyond that in the two previous models.

To fully model the land allocation decisions (assuming normally distributed—unobserved—plot-level characteristics within the observed characteristics of the operational holding) would require maximizing a likelihood function characterized by a multivariate normal distribution (in $n - 1$ dimensions, where n is the number of choices, there are six possible land uses). Each dimension of the multivariate normal would be truncated in similar fashion to prevent negative land allocations or land allocations of greater than the entire lot, with a variance-covariance structure involving nonzero covariances, since the error term

for each allocation decision is correlated with that of all the others because of the simultaneity of the decision. Because a simultaneous Tobit estimator capable of handling the number of variables and choices presented here has not been developed, several simplifying assumptions are made for the purposes of estimation. Each land use allocation decision is taken as a yes–no decision to allocate land to that choice (in effect lumping the valuation of land from other possibilities into a single category).⁴⁰ The assumption of truncated normal distributions around each land use allocation persists, but each choice is estimated in isolation from the others. The equation-by-equation estimation discards the information contained in the correlated error structure—in essence the aspect that captures how farmers make these decisions jointly. Doing so sacrifices efficiency but not consistency. In interpreting the results, however, this means that significant coefficients on endogenous resource constraints exist *without* the estimation explicitly accounting for the on-farm competition for resources that characterizes the decision choice, so the effect of constraints likely to operate on sample farms might be *understated*.⁴¹ Since operational holdings for the most part are, moreover, not spatially contiguous, the likelihood that spatial autocorrelation characterizes the error structure is small (Walker, Moran, and Anselin 2000 test for but do not find spatial autocorrelation in noncontiguous lots). The Tobit estimator is used in each equation because, unlike in Chomitz

and Thomas (2000), there is no reason to expect that this sample violates an assumption of constant variance. The partial adjustment model that led to lagged dependent variables being included as regressors hinges on past land uses (not strictly optimal under this model), known with certainty by farmers at the time land use decisions are made in time t , so no error is associated with it. The presence of lagged dependent variables does not induce heteroscedasticity in this case since the error term remains specific to time t . Endogeneity among regressors was discussed in the previous subsection, and it comes up again in the regression results in the context of specific variables. While problems with pairwise correlation among right-hand side variables were not serious, overall multicollinearity might be. Both endogeneity and multicollinearity appear in the concluding section to this chapter on future work.

Reduced-Form Model and Data. The final, reduced-form equation to be estimated is

$$s_t^i = f (s_{t-2}^i, Z^N, Z_{t-\Delta}^S, Z_{t-\Delta}^S, Z_{t-\Delta}^{H1}, Z_{t-\Delta}^A, Z_{t-\Delta}^N, Z_{t-\Delta}^N, Z_t^{TN}, Z_t^{TR}, Z_t^{COM}, t-\Delta, t_0, Z^p),$$

where s_t^i denotes proportion of land area in time t devoted to land use i . Several proportional land use equations are estimated, with a *full* set of explanatory variables in each equation for $t = 1996$, using data from farms surveyed in both 1994 and 1996 (96 households from a stratified random sample of small-scale agricultural households

⁴⁰The models above inherently do the same thing by modeling the choice as "to clear or not to clear," but in this case, information is, in essence, thrown away in each equation by making this aggregation intentionally.

⁴¹Theoretically, there could be on-farm complementarities in resource use as well, but competition for resources, especially labor and capital, is likely to dominate given the labor and credit scarcity in the area. One exception is resources for corn production that benefit livestock through feeding; there are more once the multiyear framework of the model is considered, but the presence of the lagged dependent variable capturing this mitigates this effect in interpretation of the resource constraint variables.

Table 3.1 Factors Influencing deforestation and land use, Tobit estimates

Themes and variable groups	Independent variables	Dependent variables ^a					
		Forest	Pasture	Annual crops	Fallow	Annual perennial intercrop	Perennial crops
Knowledge base							
Farmer Origin	Central West	0.05	-0.08	0.03	0.00	-0.01	0.02
	Northeast	0.05	-0.01	-0.02	0.01	0.02	-0.04
	Southeast	-2.59E-03	0.03	2.62E-04	0.02	-0.06*	-0.04
	South	0.03	-0.05	0.03	-0.01	-0.05	-0.03
Migration History	Urban Experience	0.06***	-0.05***	0.02	-0.01	-0.01	-0.05***
	# of States Visited	-0.01	0.01	-2.02E-04	-1.99E-03	0.06***	0.00
	Came Directly to Farm	-0.02	0.02	0.03**	-0.01	-0.05**	-0.02
	Time on a Ranch	-0.03	0.04	0.01	0.00	-0.18***	-0.03
	Within Project Moves	0.04*	1.33E-03	-1.99E-03	-0.01	2.80E-04	-0.04***
Literacy	Household Head Literacy	-0.02	0.03*	-0.04***	0.02	0.01	0.04**
Poverty							
Incomes	Resources Upon Arrival	0.01**	-2.81E-03	1.42E-03	-1.26E-03	-9.00E-04	-1.85E-03
	Non-Ag. Income	0.01	-0.02	-0.03	0.03	0.14***	0.02
Labor Availability	Household Size	1.91E-03	-0.01***	1.78E-03	1.44E-03	0.00	0.01**
	Proportion of Adults	0.09**	-0.13***	-0.03	-0.03	0.11***	0.06**
Land Tenure							
Farmer Status	Bought or Traded	2.08E-03	0.01	2.94E-03	8.01E-04	-0.03	0.00
	INCR and Bought/Traded	-0.19***	0.17***	-0.01	0.02	-0.10	0.02
Farm Status	Definitive Title	-0.04	0.08***	-0.01	-0.02	0.07***	-0.03
	Purchase Document	0.03	-0.06**	0.02*	-0.01	0.05**	-0.01
Transience							
1994/96 Ownership Change	Land Sold	-1.03E-03	-6.09E-04	-7.89E-05	-5.48E-04	-1.50E-03	8.41E-04
	Land Purchased	8.62E-04**	1.02E-04	-8.43E-04***	-5.08E-05	-5.11E-04	8.55E-05
		-0.01	-2.23E-03	0.01	0.02	0.19***	-0.02
Institutions							
Associations	Churches	3.91E-03	0.03	-0.03**	0.01	0.01	-0.04**
	Labor Unions	-0.06**	0.10***	-0.03***	-0.02	0.05*	0.02
		0.01	0.07	-0.06**	-0.04	0.01	-0.05
Farm characteristics							
Land quality	Water year around	0.01	0.01	-0.04***	0.03	0.05**	-0.06***
	Best soils	-4.50E-03	0.07	-0.02	-0.11**	-0.11***	0.11***
	Low fertility soils	-0.06**	0.10***	0.01	-0.04	0.02	-0.03
	Waterlogged soils	5.96E-04	0.13**	-0.03	-0.03	-0.29	-0.04
	Severe slope	-0.06***	0.09***	-2.52E-03	-0.04	-0.05***	-0.01
Initial status of farm	Farm size	-9.65E-04***	1.42E-03***	2.94E-04	4.84E-05	-1.87E-03***	-5.48E-05
	Proportion deforested	-0.21**	0.23***	-0.02	-0.13*	3.43E-03	0.12**
	Pasture investments	0.03	-0.01	-0.01	0.02	-0.04*	-0.01
Market links							
Accessibility of farm	Time to market	2.60E-04*	-2.32E-04*	-3.16E-05	1.42E-04	-5.26E-05	-1.36E-04
	Difference rainy/dry season	-1.38E-03	2.22E-03	6.51E-04	5.67E-04	1.05E-03	-3.27E-04

(continued)

Table 3.1—Continued

Themes and variable groups	Independent variables	Dependent variables ^a					
		Forest	Pasture	Annual crops	Fallow	Annual perennial intercrop	Perennial crops
Quality of transportation system	Number of types of vehicles	-1.91E-03	-0.02**	-3.88E-03	3.81E-03	0.02***	0.02***
	Difference rainy/dry season	0.03*	-0.03*	0.01*	0.00	-0.01	0.00
	Flow of vehicles	1.84E-04	-4.94E-04**	1.01E-04	7.06E-04***	5.18E-04***	-5.95E-04***
Site characteristics		-0.14***	0.12***	-0.02	-0.05	0.07*	0.05**
Chi-squared (46)		219***	211***	62*	46	133***	95***
N		96	96	96	96	96	96

Sources: ^aProportion of farmland in 1995–96 held in each category.

* Statistically significant at the 10 percent level.

** Statistically significant at the 5 percent level.

*** Statistically significant at the 1 percent level.

described in Chapter 2).⁴² Several land uses are distinguished for the purposes of this analysis, as categorized by farmers in the survey (see Chapter 2). Annual cropping land includes rotations of rice, corn, beans, and manioc (defined as an annual in this chapter despite the fact that its production cycle is longer than 12 months because it shares the same land and performs the role of a subsistence crop). Fallow land (secondary forest regrowth) is devoted to soil recuperation (by design or neglect). In addition to pastureland, the model here also distinguishes between land for pure stands of perennial tree crops (coffee, mainly), and

land in the establishment phase for perennials in which the trees are intercropped with annuals (hereafter designated “annual/perennial”).⁴³ Recall that the full description of variables included in the regression analyses, along with several reference variables that help establish farm and farm households’ characteristics, appears in Appendix A, Table A.1.

Regression Results

Table 3.1 contains the estimated coefficients and statistical significance levels for selected variables for all land use equations

⁴²The sample size is not as large as the authors would like, given the large number of regressors. Still, they found it preferable to estimate the most complete model possible on the most reliable data set available, than to cut variables or use other techniques to fill in for missing data. Based on processes better understood from analysis in this report, those steps should be possible in future work, enabling a refinement of hypotheses tested here. Reliability of land use is discussed in Chapter 2; no such cross-checks exist on recall data from the time of arrival, but the fact that the period was a milestone in the lives of many settlers lends some confidence to the recall data’s quality.

⁴³Several tests were run to assess the sensitivity of regression results to changes in the allocation of land across categories. Results supported the inclusion of annual/pasture intercropped land with pure pasture, leaving the annual category containing only pure annual production. Land containing perennial tree crops was split into two categories, one containing pure perennials only and a second containing only land dedicated to intercropped annuals/perennials.

(recall that full results are available in Appendix A, Table A.2).^{44,45} The discussion below is organized around each subcategory of Z variable (described in earlier subsections), each of which highlights hypotheses and discusses results (in *italics*) indicating when F-tests for that block of variables, available in Table A.2, tested significant. The variables relate to resource constraints (land quality and the condition of the farm upon current owners' arrival, human capital and financial assets at that time, type of tenure obtained upon arrival), and farm-gate price expectations (current tenure and variables that proxy for access to markets or trading partners). Note that hypotheses about effects of resource constraints on land allocations, as well as interpretation of results, build in researcher knowledge of context (summarized in the research site and sample description in Chapter 2) that are not precisely picked up by specific variables. Thus these regression results point to trends for which there are hypotheses, but often not clear tests, about processes (this issue is taken up in the section on future research at the end of this chapter). The most important aspects of the site context drawn on here are (1) prevalent land use practices (especially their relative factor intensities), (2) ease of marketing associated with each land use, (3) land use links with consumption decisions (especially for staple crops), and (4) the shift in prices and policy (general currency stabilization) between the 1994 and 1996 surveys. Hypotheses and interpretations center

on current conditions, so they seek to explain observed land use patterns rather than optimal ones, lessening the role here of farmers' expectations about future shifts in production or marketing regimes. The discussion below sometimes loosely refers to "more land" or "less land" in one use or another, always meaning proportionally (not absolutely) more or less, except when operational holding size is explicitly referenced. Interpretation of results also uses language implying causation, but it is the hypotheses that are about causation, which are expected to be revealed by associations found in the regressions.

Note that several variables in different categories—changes in size of operational holding (in Z_{Δ}^S), within-project migration history (in $Z_{t,\Delta}^H$), and recent change in ownership (in Z_t^{TN})—touch on the theme of transience in settlement projects. This is an interesting topic for its potential land use implications explored in some other models (see literature cited in Chapter 1, especially Dale et al. 1993; Jones et al. 1995; and Leña 1991). It also has particular policy importance given the intention to "fix" smallholders to the land in these settlement projects. A short discussion on regression results relevant for transience appears after the subsections on the Z variables.

Land Quality (Z^N)

Land quality variables include the year-round presence of water on farms and four variables indicating different types and degrees of land-related obstacles to

⁴⁴Forest and pasture columns are juxtaposed to ease identification of factors that touch on the main process of forest conversion to pasture (significant coefficients in both equations but of opposite sign).

⁴⁵Because of the partial adjustment model structure, the coefficients on the lagged dependent variables represent the shortfall from complete adjustment to optimal land use in the intervening time period. Estimated coefficients on other independent variables include these adjustment coefficients (the proportion of adjustment to the optimal that does take place in the period), but estimates of true coefficients on these are recoverable using the estimates of the adjustment coefficients (see, for example, Ramanathan 1992, p. 435). Since this discussion focuses on the direction rather than magnitude of effects, this exercise is not performed here.

agricultural production (described more fully in Chapter 2).⁴⁶ They are exogenous to farmers' 1996 decisions, considering the time path that starts upon their arrival on a farm, but they affect expected yield and hence land use.⁴⁷ It is hypothesized that lots with higher agricultural potential (less severely sloped, less waterlogged, with higher fertility) will be less forested, and that higher fertility will especially favor annual and perennial cropping systems. Extremely low fertility on farms that are still settled could also lead to less forest, but not to the same extent, given absence of resources with which to deforest. On-farm water sources will boost pasture area, since cattle production systems require plentiful and continuously available sources of water, while (rainfed) cropping systems revolve around the seasonal rains. The sample, however, is not terribly heterogeneous with regard to water availability (most farms have access year-round to water) or land quality. This, plus measurement problems especially associated with the latter, can confound hypothesis tests.

Land-quality variables considered jointly contributed significantly to overall explanatory power in all land use equations except area in forest and fallow, suggesting that land quality is more important in determining use of cleared land than in how much land is cleared. Farms with low-fertility soils plus other minor impediments to agriculture had more land in forest than farms with just low fertility. This provides some evidence that agronomic constraints

other than fertility lead farmers to leave more land in forest. (This finding runs counter to findings in Jones et al. 1995 for a different sample, and could better be tested in a sample that included more variation in fertility levels. Farms with low fertility plus other minor impediments, however, did not have more land in forest than the highest fertility soils. This could be the result of offsetting increased pressure to deforest for agriculture and to take advantage of highly fertile land. Since perennial crop growth, which makes best use of highly fertile land, is highly labor intensive, it thus diverts resources from deforestation. The significant coefficient on perennial crops for this category is in line with this interpretation. A similar offsetting effect (but in the other direction) could be behind the finding that waterlogged area favors pasture (disfavors cropping), but has no effect on forest (the hypothesized forest-saving effect washed away by the extensive nature of pasture systems). A similar argument might be made for severe slopes—the slopes do not affect establishment of pasture as much as other land uses, this in turn increases pressure on forests. The finding that farms with year-round sources of surface water did not affect pasture area but did affect propensity to shift product mix toward perennial systems (establishing new perennials intercropped with annuals) is more perplexing and deserves closer examination. It does suggest that water scarcity in the area in the dry season is not severe enough to affect herd size (due either to

⁴⁶The omitted land-quality variable was the type judged by soil scientists to be the most prevalent in the area, having low fertility plus some not severe problems with rockiness and slope.

⁴⁷These factors are likely endogenous to farmers' decisions to settle on a particular lot but not always. INCRA randomly assigns land to those settling land through its official channels (nearly a third of our sample, although informal bargaining even at this stage may well occur). From field interviews, the primary criterion for "squatters" who short-circuit the INCRA process is contiguity to existing settlements, and for those who purchase land, access to markets. The land quality within the projects, while heterogeneous, does not encompass the most fertile soils in the area (already settled when these projects were open). All this said, land quality probably does factor into settlement decisions.

prevalence of year-round water, or broader access to water via the herd/pasture sharing arrangements described in Chapter 2).

Initial Farm Status ($Z_{t,\Delta}^S$)

These variables control for condition of the lot when the current farmer arrived in order to isolate effects of current owners' decisions. A priori, it is difficult to formulate specific hypotheses about these variables without more detailed information about land transfers, especially factors influencing whether farmers buy or sell forested versus cleared land. Net of the effect of transfers, larger lots are expected to have higher proportions in forest, given that resource constraints limit the amount deforested per year (controlling for time on lot and time of initial lot opening). Farmers whose lots have higher proportions of land cleared upon arrival have marginally greater incentives to intensify land use on cleared area by planting perennial crops and intensifying cattle production. To the extent that buying land in the project represents a new and significant financial outlay (recall that initial migrants received land at close to no cost from INCRA), and that this act is controlled for in the regression, these net-of-transfer effects may dominate. But the "land use composition" of land either bought or sold can cause other types of effects. If land values accurately reflect future profit streams (and incorporate clearing costs for forested land and factor in the degree of future land degradation), then time constraints, imposed by clearing or land use management, could figure prominently in the decision about whether to buy or sell forested or cleared land. The desire to avert potential fines for surpassing limits on deforesting more than 50percent of one's lot could shift the result of the farmer's calculus in the direction of more forest. Rather than derive specific hypotheses, this report looks to regression results to suggest what effect dominates in this sample. In addition, existing on-farm investments in pasture are expected to lower current farmers'

costs of investing in that area; the investments could boost area in pasture but may themselves be evidence of a more intensive pasture management system, so the effect here is also ambiguous.

Farmers who initially occupied larger lots converted more forest and devoted more land to pasture and less to annuals/perennials. Farmers initially occupying lots with larger proportions cleared also had less in forest and more in pasture and pure perennials.. The findings point to a propensity to use larger lots for pasture expansion (responding less to recent exogenous price signals favoring establishment of perennial stands), controlling for whether the larger lot size emanated from earlier initial settlement. They also point to a tendency to diversify into more land-intensive uses on farms settled with less forest available. Previous investments in cattle production infrastructure did not influence area in pasture directly, but it did decrease area in annuals/perennials. This provides indirect (and inconclusive) evidence that previous pasture investment encourages more land-intensive use of pasture, and by lowering costs shifts the balance of benefits from different land uses toward pasture (seen in less responsiveness to relative prices favorable to perennials).

Farmer Knowledge Base ($Z_{t,\Delta}^H$)

Farmer knowledge about agricultural practices and available technologies, biophysical processes affecting this (especially familiarity with their own natural resource base), and opportunities for trading output (market and marketing information) are thought to influence land use allocation via expected profits. The region of origin of settlers has been posited as an important force, particularly during initial settlement of the area, because settlers bring with them agricultural practices from other agroecological zones, which may be inappropriate for study areas (Cunha and Sawyer 1997; Pichón 1997). The tendency of settlers of similar origin to settle in the same areas

within projects might have created opportunities for local trading and eased some of the difficulties faced in establishing new farms (Sydenstricker 1998). Migration history is also considered important in identifying settlers with different asset bases, who move for primarily different reasons (out of desperation versus a desire to capitalize on profit opportunities in frontier areas) (Leña 1991). Some indication of schooling is often used as a proxy for a farmer's ability to assimilate knowledge about technologies from a greater variety of sources, due to some combination of expanded knowledge and greater exposure.⁴⁸ These factors are examined in turn.

Origin. The effects of imported agricultural practices are not likely to persist in mature settlement projects such as these, where information about the resource base and prevalent agricultural practices are more readily available to new migrants (via demonstration or discussion). To the extent that social networks based on this factor persist amid considerable farmer turnover, this could improve farmers' abilities to respond to market signals or expand trading opportunities. A priori it is difficult to say which social networks would perform which function, and with what effect on forests, although farmers from the more economically vibrant south and southeastern regions might retain some advantage in knowledge of (or connections to) relevant markets and marketing channels.

Block F-tests indicate that the region of origin matters for allocation of land to pasture and annuals/perennials, but not for forest per se. Farmers originating from the Southeast region had proportionately more

land in annuals/perennials than the omitted category (farmers from the North, or Amazon region), which lends some support to the idea that those of Southeast origin had better links to broader markets. Farmers originating in the Southeast also had proportionately more land in pasture than did farmers from other regions, especially Central-West (revealed by the F-test for the pasture equation; selection of the omitted variable obscures the significance of this relationship). Given pasture's importance to agriculture in the Southeast during the primary waves of migration, this could provide support for the "imported practices" hypothesis, given that land in pasture does not usually revert to other uses. But because the lagged dependent variables in the equation would pick up much of this effect, it more likely supports an "improved access to market" hypothesis. Farmers from the Amazon did not have more land in forest, despite extractive traditions, which seems to provide additional evidence that imported practices, although perhaps once important to the success or failure of a farm, hold less sway now.

Migration History. Households with some urban experience prior to arrival on the lot are expected to be more aware of potential employment and market opportunities. In the long term, this can have ambiguous effects on levels of forest, since profits earned could be permanently diverted from agriculture or reinvested in agriculture, depending on broader economic conditions (this is discussed more fully in Chapter 4, on the bioeconomic model). In the shorter term, the effect should be to divert resources away from

⁴⁸All "knowledge" variables are measured in terms of the primary decisionmaker, or household head. For migration, this abstracts away from potentially important, but impossible to capture here, effects of household strategies that involve different paths by different individuals, potentially important for labor availability and for the purposes here, capital accumulation. For literacy, education of other household members may importantly influence the household's ability to adopt new techniques, but since this education may have occurred in the project (along with land use decisions), it is endogenous and cannot be used as a regressor.

agriculture. While this model focuses on land uses in the shorter term (given the presence of the lagged dependent variables), it may capture effects of returns on investment realized only within this window. The effect is ambiguous; regression results may suggest a narrower range of likely scenarios. In this sample, “transience” (that is, frequent movement) of farmers before coming to the project may reflect either entrepreneurship or persistent poverty: regression results may indicate which effect dominates. Experience within the project prior to settling on one’s own lot can influence land use patterns, as is the case with source of origin, more because it indicates continuing social networks than because farmers are exposed early on to different land use practices and agronomic conditions.⁴⁹ Social networks can improve farmers’ abilities to capitalize on market conditions if such networks also facilitate access to markets. Such access may favor investment in annual/perennial systems, or it can create more local trading markets that relax on-farm resource constraints and favor investment more generally. There is some ambiguity regarding those who moved frequently within the project before settling. Were these moves made out of success or failure? (But given the general appreciation of land values over time, the fact that these farmers are still in the project may indicate success.) To the extent that moves for either cause are foreseen by farmers, they work against investment in land uses whose benefits take longer to realize (such as perennial tree systems, which, in any case, require investments that farmers who are at the edge of profitability cannot afford).

Pre-project experience mattered (according to F-tests reported in Appendix A, Table A.2) for all land uses except those

most tied to subsistence farming (annuals and fallow). Farms headed by individuals with previous experience in urban areas had larger proportions of land in forest and less in the pasture and pure perennial categories—indirect evidence that nonfarm activities were drawing resources out of agriculture. Farmers with wide migration experience (having passed through a relatively large number of states before arriving at the colonization project) held more land in annuals/perennials, suggesting that this group had greater ability to respond to market signals. Within-project experience, on the other hand, was significant only for land uses involving annuals (annuals alone and annuals/perennials), and varied with type of experience. Farmers whose first stop was on their own lot had more land in annuals and less in annuals/perennials, in keeping with their more limited access to social networks that would aid the farmer in capitalizing away from production of subsistence crops or ease access to markets. Those stopping first on a large cattle ranch maintained less land in annuals/perennials but did not have significantly more pasture, perhaps indicating a role for exposure to more land-intensive cattle technologies (not necessarily part of common knowledge), although this is speculation. Farmers who moved frequently within the project had more land in annuals and less in pure perennials, supporting the hypothesis that farmers were more likely to move frequently as a result of failure rather than success. This is in line with a finding that the primary wave of settlers had to sell out to wealthier second-wave settlers to cover debts (Leña 1991). Whether those remaining in the project were relatively more successful than the ones who were no longer available for interview or whether they

⁴⁹ Similar to variables capturing the effects of an individual’s region of origin, these factors may have been critical in determining who succeeds on their farm, and thus who appears as a respondent in this sample.

stayed in the project because of relatively lower migration costs remains unknown.

Literacy. Households headed by literate individuals (able to read and write) are expected to have a comparative advantage in document- and information-intensive production and marketing processes. This should mean less reliance on annual cropping for subsistence needs and greater agility vis-à-vis market signals (in this context, indicated by more land in annuals/perennials). The effect could be mitigated by (endogenous) education of other household individuals (see footnote 48).

Farms operated by individuals who could read and write had significantly less area in annuals and significantly more in pasture and pure perennials. The finding regarding annuals is as expected; the finding vis-à-vis long-standing land uses, requiring greater investment, may indicate that the literate benefit from a greater knowledge of technology. Literate farmers may or may not know about price conditions earlier; these results suggest that they have no better information at the time planting decisions are made.

To sum up, regression results suggest that some aspects of the farmer's knowledge base are linked to market responsiveness and others to on-farm capitalization and technology use. Exposure to a broader range of experience outside the project (before migrating to the project) is associated with greater responsiveness to recent market signals in the agricultural sector and opportunities in the urban sector. Exposure may create familiarity with markets or generate continuing social networks that facilitate a direct link with markets. Either path could lower costs associated with acting on exogenous prices, and therefore increase farmer responsiveness. The urban exposure need not—but does, in this sample—act as a net draw of resources from agriculture (perhaps via investment or labor opportunities). Within-project contacts (living with another settler before arriving on one's own

lot) seems to improve a farmer's chances of moving beyond subsistence farming, perhaps because the farmer has become familiar with and invested in a range of less commonly used technologies. Literacy also helps in the general investment/capitalization process, but in itself it gives farmers no extra advantage in knowing and responding to market signals, within the timeframe of the agricultural year captured here. Findings on frequency of movement are discussed in the subsection on transience.

Farm Household Asset Base ($Z_{t-\Delta}^A$)

For the poorest farmers, a sufficient asset base to assure subsistence is the overriding goal. Once this is attained, poverty can still limit farmers' options for investment/capitalization paths, affecting land use and environmental outcomes (Reardon and Vosti 1995). The initial land base having already been discussed, this discussion centers on the effects of household financial assets and labor resources upon arrival.

Farm households having more financial and labor resources upon arrival have the wherewithal to get about the business of forest clearing more quickly than their less-well-off neighbors; those with a relatively abundant supply of labor may have the option of establishing labor-intensive agricultural activities. Such additional resources can create opportunities for diversifying off farm or even outside of agriculture. Those arrivals who have steady nonfarm income may also have a social network, with similar effects to those seen above. The effects of lasting social network connections would most likely be seen in the equation, since other effects could be partially or wholly picked up by the 1994 land use allocation variables.

Resources upon arrival mattered for all land use equations except secondary forest fallow (F-test in Table A.2). Households arriving with above average amounts of financial reserves had more forest in 1996, but these resources did not affect use of cleared land. Although this finding was not

expected, it could have many explanations: (1) Wealthier households are more likely to invest off farm or to be based elsewhere and holding land for speculation or diversification purposes. (2) Households with secure sources of off-farm income upon arrival had larger proportions of land in annuals/perennials. This agrees with the hypothesis that an off-farm social network leads to market connections, although the source of that income is unknown. (3) Households with more members had significantly more land in pure perennials and less land in pasture; those with a larger share of adults had more land in forest, annuals/perennials, or pure perennials and less land in pasture. Initial labor availability seems to have a continuing impact on land use. The longer time frame of the productive cycle of perennial tree crops and their labor-intensive nature may lock in household labor resources over time once the household has committed to this land use. Use of labor resources for perennials competes with and helps define land clearing. There are costs to clearing more land than can be usefully used, since it degrades if neglected, so households concentrating on perennials tend to have more forest. Households short of labor early on, on the other hand, continue to opt for more extensive livestock production systems.

Land Tenure

The causal link running from land use to land tenure in the Brazilian Amazon has been cited as an example of policy-driven deforestation—smallholders must clear land in order to gain secure access to it (Mahar 1989; Schneider 1994). For smallholders, risk of expropriation drops as settlement projects mature, but degree of tenure security can affect land value to the extent that any risk remains. More secure land tenure, however informal, can also open doors to particular lines of credit. Two sets of land tenure variables are examined here. The first set identifies the manner in which 1996 respondents first obtained land

in their 1996 operational holding (via INCRA, by squatting, through trade or purchase, or some combination of these). The second set measures the type of land title in the possession of the owner at the time of the 1996 interview. The peculiarities of the land tenure system (legal restrictions as opposed to current practices on use of forest, sale of property, and evolution of title from provisionary to definitive) are described in Chapter 2. The fact that the effect of these variables on land use was examined in 1996 lessens the case for endogeneity of land tenure upon arrival.

Land Tenure 1 ($Z_{t,2}^{TN}$). Farmers who owned their lots in 1996 can be distinguished by the way they acquired them: (1) those who gained land via illegal squatting in forests; (2) those who received lots from INCRA and remained on them; (3) those who received lots from INCRA, maintained those lots, and then purchased others; and (4) those who purchased land outright. The presence of (1), (2), and (3) in the 1996 sample could signal different degrees of success: all of these lot holders were more likely to be resource poor upon arrival, yet they have not disappeared from the project. The effect of the resources thought to influence the time path of land uses would, like the ones above, be expected to be correlated with the lagged dependent land use variables. Net of this, a pathway for a persistent effect on 1996 land uses would be via farmer characteristics—such as entrepreneurship or management skills—picked up by these relative indicators of success in farming. Since the variables are not clearly enough identified (or the effect of these skills on land use choice well-known), testable hypotheses could not be set up.

Deforestation and land use patterns for lot purchasers and those having only an INCRA lot did not differ significantly, indicating no persistent effect of mode of acquisition on subsequent land use. Owners who received one lot from INCRA and later expanded have more area in pasture and less in forest. Given the previous discussion on

the composition of land that gets transferred (forested versus cleared land), this finding should be considered in conjunction with another—the finding that owners who bought additional farm area (regardless of mode of acquisition) had significantly more land in forest and less in annuals. This topic is taken up in the section on transience below.

Land Tenure 2 (Z_i^{TN}). More secure tenure helps relax liquidity constraints, easing capitalization and movement out of subsistence cropping. To the extent that even a slight risk of expropriation remains, due to insecure tenure, area in perennials with long life cycles would be expected to decrease.

Land tenure in 1996 mattered only for pasture and annual/perennial equations (F-test in Appendix A, Table A.2). Farms with definitive land title in 1996 had higher proportions in pasture and annuals/perennials. Having a purchase document to prove land tenure, however, reduced area in pasture and increased area in annuals and annuals/perennials. The findings do not provide clear support for the hypothesis that tenure acts primarily via credit. Most government-sponsored credit schemes geared toward small farms would not distinguish between definitive title and purchase document, but other sources might. This could explain the differing results for these tenure categories regarding pasture. That annuals/perennials appeared to be significant only during the establishment phase seems to indicate that tenure helped increase the supply of short-term human and financial resources available to respond to market signals. This finding could provide evidence that risk of eviction is having an influence, although the timing of the switch to economic conditions favoring perennial crops makes this relationship harder to pinpoint.

Transportation and Market Access (Z_i^{TR})

Access to markets is often cited in the literature as an important factor affecting land

use, especially for isolated farm households and for extractive and other products that perish quickly without processing or refrigeration (Singh, Squire, and Strauss 1986; Vosti and Witcover 1996b). But not just distance from market affects market access, but specifics of local marketing institutions and chains for particular products as well.

Farmers who have shorter traveling times to markets and farm-gate prices closer to local marketplace prices are expected to garner more benefits from clearing land, so they tend to have less land in forest and more in annuals/perennials. To the extent that they already have land in pure perennials, they may have more forest (because of the labor constraint). If farmers must travel a greater distance to markets or face a high seasonal differential in the time it takes to get to markets in the rainy season versus the dry season, the household calculus could tip toward planting more subsistence crops for food security reasons.

Controlling for time to market, the volume of vehicular traffic near the farm can indicate increased options for arriving at the marketplace or for trading outside the physical marketplace. More modes of transport—not just more traffic but more types of vehicles available for transport of goods—passing the farm more frequently can be expected to promote production of perishable items, such as byproducts of cacao, tropical fruit, coffee, or milk, with consequent increases in areas dedicated to perennials, pasture, or both.

Transportation variables as a group had a significant impact in all equations but forest and annuals. Still, farms with higher travel times to markets had more land remaining in forest (as expected), and less in pasture. Seasonal fluctuations in transport time to market did not influence land use patterns at all, with the expected effect on annuals for food security reasons absent. Farms with larger numbers of transportation modes passing their farm in the dry season had more land in pure perennials and annuals/perennials and less in pasture.

This supports the hypothesis about perennial products, but not milk, perhaps because labor competition on farms precludes significantly higher pasture and perennial area response, or because milk sales depend on the passing of a particular type of vehicle. Seasonal differences in the number of modes of transport also influenced land use; greater differences in available modes led to larger amounts of land left in forest and allocated to annual crops and less area in pasture, so the food security hypothesis plays out more regarding modes of transport than time to market. Sheer volume of traffic on roads passing farms meant more land in annuals/perennials and fallow but less in pure perennials and pasture. The findings regarding annuals/perennials and fallow may indicate that higher traffic volume creates a less-specialized link to markets, but why this should affect secondary fallow and not forest, or area in pure perennials or pasture, is not clear.

Local Institutions/Community Associations (Z_f^{com})

Social foci facilitating farmer interaction (principally associations, churches, and unions, as described in Chapter 2) create conduits for information flows generally, including data about markets and technologies. Most associations have more frequent communication with entities outside than within settlement projects (Sydenstricker 1998). Farmers' associations are often geared toward marketing; they reduce input and transportation costs for farmers by increasing the volume of units purchased and sold. Evangelical churches often provide an impetus for work parties arranged around individual or collective projects (land clearing or road improvements). Both types of organizations are repositories of specialized human capital (particularly organizational and planning skills). Government-sponsored labor unions were less prevalent. They seemed to have fewer well-defined tasks and were not investigated much because they did not form as a result

of local farmers' decisions (Sydenstricker 1998).

All these venues should provide an "in-project social network effect," with a priori ambiguous effects on land use, in line with findings regarding farmers' knowledge base, easing constraints in a way that supports farmers' capitalization process. Farmers' associations may be more likely to help establish generalized market links, which would show up in results as more land in annual/perennial crops.

Community organizations mattered in every equation except fallow (F-test in Appendix A, Table A.2). The presence in the neighborhood of a farmer association or evangelical church significantly decreased the proportion of land dedicated to pure annual crop production, somewhat in line with the capitalization hypothesis (but with no clear emphasis on pasture versus perennial crops, which could in turn cause important differences in forest use). The presence of a labor union office also decreased reliance on annuals, but it increased the proportion of land dedicated to pasture and annual/perennial crops at the expense of forest and annual crops. This suggests a capitalization process skewed toward pasture accumulation plus responsiveness to recent market signals. Closer examination of the workings of these organizations would be needed to discover why this might be so.

Project-specific Characteristics (Z^p)

The conjunct of factors picked up by the project-level dummy is expected to show less forest, more pasture, more perennials, and more annuals/perennials for Theobroma than Pedro Peixoto, given greater proximity to market centers, higher local population density, and more government programs geared toward pasture and particular perennials.

Farms in the Theobroma colonization project (the older of the two, the one located closest to markets along the major north-south all-weather road, and the one located

in the pro-agricultural growth state of Rondônia) had significantly smaller proportions of area remaining in forest and greater area in pasture, pure perennials, and intercropped annuals/perennials.

Transience

Changes in size of operational holding (in $Z_{t-\Delta}^S$), within-project migration history (in $Z_{t-\Delta}^H$), and recent change in ownership (in Z_t^{IN}) may also affect deforestation and land use practices. Field research distinguished land sellers and land purchasers. Land sellers are likely to be doing so to cover liquidity needs (short-term debt as the result of illness, for example), or because demographic shifts make management of the whole farm impossible. Controlling for 1994 land allocation, the result of sales from household labor attrition would be less land in annuals/perennials or pure perennials. Land buyers may prefer to purchase primarily forested or cleared land, according to trade-offs already outlined, so the effect here is ambiguous. Effects of recent ownership changes are also ambiguous, but if the transfers were foreseen or the result of distress, they may be associated with less land in pure perennials.

Deforestation and land use patterns for those selling land did not differ from those whose farm size did not change. Land buyers, however, tended to have larger proportions of land in forest (and less land in annuals) in their 1996 operational holdings, but recall that this is controlling for an important subset of owners who expanded holdings after initial settlement by INCRA. The latter group had more pasture area and less forest. This suggests different strategies or capital constraints among those buying land. Some buyers had a preference for land already cleared by original settlers (indicating an intention to immediately farm on all cleared land), and others preferred land in forest (indicating profit-making plans involving future agricultural expansion). While a number of moves prior to arriving in the project seemed to be associ-

ated with success in farming, several moves within the project before settling on the current lot carried more of the characteristics of distress sales. This could indicate that successful farmers remaining in the project are less likely to “trade up” in terms of lot location than to expand landholdings.

Farms that changed ownership during the 1994–96 period had proportionately more land in annuals/perennials, but the share of area in forest was not affected. This may suggest that new owners have a freer hand to respond to market signals, taking the state of the lot upon arrival as given.

General Conclusions and Topics for Future Research

Land use decisions of farmers who are well integrated into broad markets are not likely to be influenced by the factor endowment and social interaction variables discussed here, and the effect of distance to market can be captured entirely by the transportation costs to that market. But such analyses assume that the “reach” of the market encompasses all actions relevant to the dynamic expansion of the agricultural frontier into forest areas, which may not be the case, especially at the agricultural frontier.

Information on recent land use patterns in the regression confirms the prevalence of a pasture/forest trade-off and land use trajectory from, for example, annuals to pasture, as discussed in Chapter 2. Given that farmers are partially adjusting toward optimal conditions along such trajectories, variables hypothesized to affect farmers’ profit expectations by easing their access to markets or their on-farm resource constraints mattered for specific land use patterns. Because of the lagged variable controls, the precise effect of levels of on-farm resource constraints on land use patterns was not directly tested for. Information about how prevalent production technologies use land, labor, and capital (Chapter 2), however, suggests how on-farm constraints can lead

to competition for resources across land uses. This information about technology requirements aided plausible interpretations about results of particular variables across equations. Similarly, knowledge about the substantial relative price shift between surveys made it plausible to use annuals/perennials as an indicator of responsiveness to relative prices in regional markets—a characteristic otherwise difficult to ascertain. Given these shortcomings (and those discussed below), the direction rather than the magnitude of effects from regression results were considered, with interpretations that were in line with results. Tests for how levels of resource constraints play out in a dynamic fashion in land use choices are left to Chapter 4 on the bioeconomic model.

In addition, findings about the differing effects of different aspects of land quality—especially fertility versus other characteristics such as slope and rockiness—are an important addition to a growing literature on this topic, suggesting that a focus solely on fertility might be misplaced. Still, the finding is watered down by the possibility of errors in measurement of, or insufficient variation in, land quality.

More striking perhaps was the important role played by social networks, established either prior to arrival in the project (as part of the “knowledge base” of the farmer) or within it (in local organizations), in either case easing access to markets or on-farm resource constraints, thus affecting land use patterns and ultimately deforestation. A shortcoming of this approach is its inability to capture endogenous change in the knowledge base—learning—which surely affects land use patterns.

The examination of market access itself was innovative in that it allowed for markets, in effect, moving to farmers, and for transport options to be distinguished from distance to markets. These innovations picked up important land use effects, including one involving food security, which a more conventional measure missed.

Finally, the results about changing land size and transience of farmers within projects and before they arrive point to important economic events on the dynamic expanding frontier that are overlooked by analysis that focuses solely at the farm level. These results have implications for poverty and deforestation, and even point to some topics that, if more closely examined, could shed light on what those implications are. Along with the social network findings and the information on the prevalence of local sharing arrangements (Chapter 2), they point to a need to further investigate the role of these local conditions and their market-like functions in the absence of fully integrated markets.

Model Limitations and Their Implications

While the reduced form regression model and the field data set have some interesting features for testing land use decisions, they have serious shortcomings as well. The panel sample is small, and there was sample attrition. Beyond the farms that were sold out of the sample, there is no reason to expect that sample attrition (due to missing values) had a structure that biased land use results; yet this remains to be tested. Although there is no reason a priori to expect problems with the error structure, endogeneity, autocorrelation, or heteroscedasticity could still present difficulties because of omitted variables, errors in measurement, more complicated spatial lag or spatial regime effects, or a different interpretation of the presence of the lagged dependent variables (from an adaptive expectations model, for example). This means that significance of coefficients at the 5 percent and surely the 10 percent levels should be interpreted with caution. It would be unusual, however, if efforts to account for patterns in error structure changed the conclusion of a significant relationship for variables found significant at the 1 percent level in this report. Aspects of the model specification and its estimation dilute its ability to test

critical hypotheses about the effects of levels of household resource constraints on land use patterns, given specific off-farm institutional conditions. “Induced” multicollinearity between initial resource allocation and the lagged dependent variable is one example of this; the inability to exploit the correlated error structure across equations (or in a more fully specified set of input equations) is another; and the lack of a consumption equation to complete the system a third. The dynamic structure of the theoretical model justifies the presence of “initial resource” variables, but insofar as these variables are proxies for resources concurrent with land use choices, an instrumental variables approach (and different inference testing) is called for. Finally, while the theoretical approach justifies the types of variables included, it does not suggest a specific functional form, so the way the variables enter the model is somewhat ad hoc, an exploratory technique to pick up strong linear relationships among variables as specified.

From Multivariate Regression Analysis to the Farm-level Bioeconomic Linear Programming Model

Multivariate analysis confirms the importance of farm and farm household points of departure in determining 1996 land use. It also confirms the importance of resource quality and marketing costs and the need to pay close attention to sequences of land uses to obtain information about technological choice and biophysical processes. The next chapter includes some of the factors that matter most in identifying deforestation and land use and builds them into a comprehensive, farm-level model. The model can examine on-farm resource competition (for labor, land, and capital) among land uses in an institutional and policy context, where prices formed in the marketplace are modified by institutions, policies, and transport costs on the way to the farm gate. It does so for a farm household, like the one in the theoretical model in this chapter, looking out into the future to establish the optimal time path of action to maximize profits.

CHAPTER 4

A Farm-Level Bioeconomic Model

To evaluate the net effects of particular policy and technology changes on deforestation, land use, and farm household income requires an analytical tool capable of explicitly considering (1) both the biological and economic forces at work in determining deforestation, land use, product mix and technical choice on farms; (2) competition at the level of the operational holding for labor, land, and cash; and (3) the forward-looking, profit-maximizing nature of smallholder decisions. This section describes a farm-level bioeconomic model, principally its structure, including treatment of soil productivity and degradation and initial conditions, based on the sample area. The next two sections present a baseline simulation using those initial conditions, emphasizing results on deforestation, land uses, use of family and hired labor, and income, and examining the sensitivity of results to certain key model assumptions. The following section presents the same type of results from model simulations run under a series of policy-relevant conditions. A final section outlines key assumptions underlying the model, including choice of objective function and time horizon, and discusses their implications for research results and their possible modification in future work.

Whole Farm Optimization Model: A Description

A linear programming (LP) model was developed to explicitly account for the biophysical and economic factors determining farmers' deforestation and land use decisions. Bioeconomic models are being used increasingly to examine issues involving the interplay among economic and biophysical factors and processes. Some of these models focus on particular geographic units (such as watersheds, fishing grounds, or rangeland areas) and examine how individuals singly or collectively respond to and manage multiple biophysical processes to generate human welfare, with consequent changes in the stocks and qualities of natural resources (Barbier 1996; Barbier and Bergeron 1998, 1999; Bouman et al. 1998; Kruseman et al. 1995; Ruben, Kuyvenhoven, and Kruseman 2001; Sanchirico and Wilen 1999, 2001; Smith 2001). Bioeconomic models explicitly identify and account for changes in biophysical input (for example, soil nutrient) availability, their impact on crop growth, and how this affects economic decisions about land use management, which in turn alters input stocks for the next period. Traditional farm accounting models (as in Gittinger 1984) and activity analyses often overlook or oversimplify biophysical factors or the way in which they affect, and are affected by, management decisions over time (Tomich et al. 2001).⁵⁰

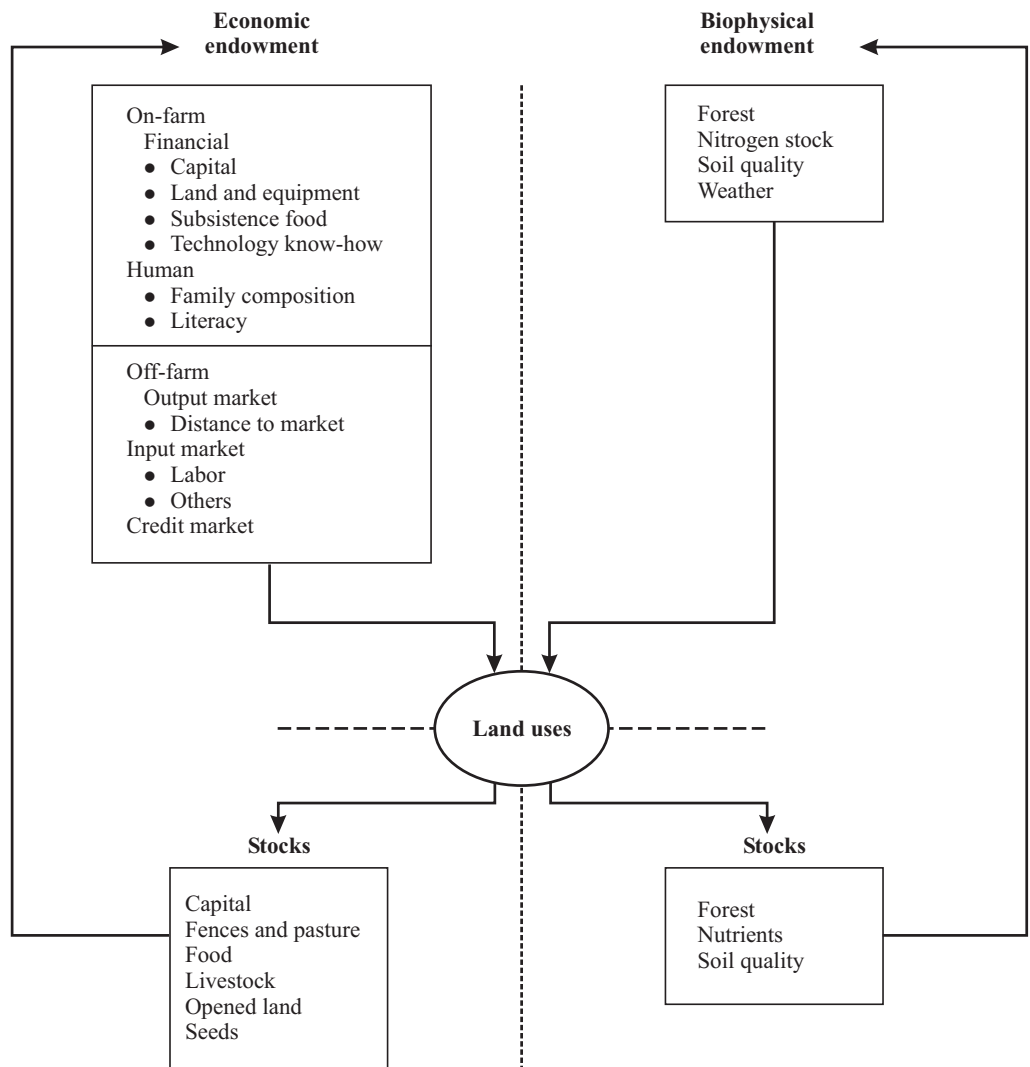
⁵⁰For a review of farm modeling approaches used in the context of deforestation research, see Kaimowitz and Angelsen 1998.

Structure of the Model

Figure 4.1 depicts the model’s basic structure. (An algebraic presentation and description of the model appears in Appendix B.) The model characterizes the resource use decisions of an archetypical farmer who is endowed with land, labor, and cash. The farmer’s objective is to maximize the discounted value of the household’s consumption stream over a set time horizon via production of agricultural and extractive products for home consumption and sale. The farmer faces an array of technology- and

endowment-related constraints (including soil quality and how management changes it) and must consider the financial benefits of various activities, including sale of household labor or hiring of nonfamily labor for agricultural purposes. In the model, the farmer knows (1) all relevant production parameters for alternative systems and the input use and yield implications of alternative ways of producing them; (2) the effects on soil nutrient availability of different cropping systems and the implications for crop yields of changes in

Figure 4.1 Bioeconomic structure of the model



nutrient availability; and (3) input and output prices, including costs of labor hired in and returns to family labor hired out. The model thus does not account for risk. As depicted in the bottom section of Figure 4.1, future land use decisions are conditioned by past decisions, which alter the composition and quality of household resources available to support economic activities. While the model allows off-farm labor activities, it does not incorporate nonagricultural investment (for example, schooling). It also does not explicitly include preferences (a utility function), but does include a subsistence constraint, in that resources to meet minimal consumption needs (as identified by household demographics and local food habits) must be available in each period. Since leisure time in each period is imposed as part of this subsistence constraint (again based on usual patterns in the area), household consumption of leisure does not shift as incomes change. Family demographics, farm size, and farm ownership remain constant over the time horizon, implying that households with these characteristics will be managing these farms throughout the period (and any transfer is costless in terms of resources available, including time). The time horizon in simulations in this report, unless otherwise stated, is 25 years, sufficient time to capture farm-level adjustment to scenarios presented here as well as to assess the model's stability under these conditions.

Cleared and forested land can be put to various types of uses, but their profitability will be conditioned by yield drop-offs as soils degrade or the increased cost of correction via purchased inputs. Because of the biomass burn, land taken out of forest can initially go into any production activity without need for purchased inputs. However, if land is put into annual crops, severe yield declines will occur after three years at most. Without the addition of external inputs, farmers will be forced to switch to fallow or to pasture.

Initial Conditions

The model has an explicit set of farm and farm household characteristics that indicate starting points, in terms of land already in use (for example, area in pasture) and farm- and household-specific constraints (for example, family size), that influence allocation of land, labor, and cash to alternative land uses. Table 4.1 presents initial conditions for two types of farms/households: farm type A is closer to markets, better capitalized, and smaller, but it has slightly more working age adults and dependents; farm type B is farther from markets, poorer, larger, and its household size is smaller (but has a higher ratio of working age members to dependents).⁵¹ At the time of the study, land use on type A farms averaged 28 percent of farm area already cleared, broken down into 15.0 percent (9 hectares) in pasture, 4.2 percent (2.5 hectares) in annual crops, 2.5 percent (1.5 hectares) in

⁵¹Initial conditions were derived from field data collected in 1994 from the Pedro Peixoto settlement project in Acre. Farms were clustered on the basis of characteristics deemed to be exogenous to farmers' land use decisions as characterized by the model (for example, soil type, distance to market, and age of settlement of land). Each cluster can be thought to represent a farm type. The average farm and household characteristics for a *relatively well-situated farm type* in terms of access to markets (farm type A) were used as the initial conditions to generate the model baseline. This cluster of farms was dominated by soil types of medium quality—that is, soils with some inherent restrictions to agricultural productivity (fertility problems, mild slope, or rockiness, or a combination of these problems).

Table 4.1 Farm and farm household initial conditions for the bioeconomic model

Characteristics	Baseline values for farm types A and B	
	A	B
Markets, transactions, and prices ^a		
Labor transactions		
(maximum number of person-days/month)		
Hired	15	10
Sold	15	10
Milk quota (maximum liters sold/day)	50	0
Product price wedge ^b (%)	15	20
Input price wedge (%)	20	25
Cattle price wedge (%)	25	30
Agricultural credit (reals)	0	0
Technology available ^c		
Rudimentary	(v1)	(v1)
Improved	(v2)	(v2)
Brazil nut production (latas/hectare ^d)	1.0	1.50 ^e
Brazil nut production (person-days/lata)	0.5	0.5
Transportation		
Transport time (days/round trip to market)		
Ox, dry season	1.52	.88
Ox, rainy season	2.03	3.83
Truck, dry season	0.63	1.00
Truck, rainy season	0.78	1.00
Transport cost (round trip to market)		
Truck (R\$)	91	104
Household assets, liquidity, and expenses		
Food storage capacity (kilograms)	2,000	2,000
Minimum near cash maintained (reals/season)	500	500
Initial cash balance (reals in year one)	250	250
Minimum expenses (reals/month)	118	88
Initial forest reserve (hectares)	43	67
Initial cleared land (hectares)	17	23
Adult male family laborers	1.63	1.42
Other family laborers (adult male equivalents)	1.47	1.05
Sample size	25	26
Share of sample (%)	43	45

Source: IFPRI/Embrapa/ASB field data.

Notes: Farm type A is closer to markets, better capitalized, and smaller, and it has slightly more working adults and dependents. Farm type B is farther from markets, poorer, larger, and its household size is smaller. V1 refers to traditional agricultural activities that make little use of purchased inputs; V2 refers to intermediate activities using some purchased inputs

^aUnless otherwise stated, all prices are reported in terms of 1996 Brazilian reals.

^bFarmers cannot buy and sell particular commodities, inputs, or livestock at the same price in the marketplace; limited volume, market links, and product quality issues usually establish a “wedge” between product sale and purchase prices. These price “wedges” were estimated from field information and are included in the model as initial conditions and maintained throughout.

^cFor descriptions of production technologies, see Appendix B.

^dA lata is a unit of measure for Brazil nuts and other products in the Amazon: 1 lata = 10 kg. or 18 liters fluid measure.

^eHigher productivity in Brazil nut collection on larger and more distant farms reflects higher natural productivity of Brazil nuts in larger forest blocks.

perennial crops, and 6.6 percent (4.0 hectares) in secondary forest fallow; type B farms had slightly less cleared land and were slightly more dependent upon pasture. Half the sample households fell into each category. This report focuses on type A farms because trends suggest steadily improving links to markets for farmers in these settlement areas (see Carpentier, Vosti, and Witcover 1999 for results regarding type B farms). The model uses relative prices from 1994, except for policy simulations that use 1996 prices. It implicitly incorporates a model of price expectations in which the farmer expects the price vector relevant for the current agricultural year to match that of the recently finished year for outputs, supplemented by expectations of

input prices taken from prices observed close to actual time of purchase or use.

Soil Quality

Soils in the area, while generally of poor quality for agricultural purposes, are heterogeneous in ways that affect yields and the length of time agricultural activities can be practiced on particular plots of soil; they require different types of external inputs to correct them (Lewis et al. 2002). Results from soil chemical tests from the project area are summarized in Table 4.2. Based on the tests, three categories of soils (good, medium, and poor quality) were identified.⁵² Amendments to correct for inherent soil infertility or other problems cost money and time to apply, and they may benefit weeds as well as crops, implying higher

Table 4.2 Three soil quality groups representative of Pedro Peixoto soils

Soil Quality	pH	P (mg/dm ³)	Cmole/dm ³							v (%)	m (%)
			K	Ca	Mg	S	Al	H+Al	T		
Poor	4.4	2	0.05	0.2	0.1	0.35	2.3	5.11	5.46	6.4	86.8
Medium	5.1	5	0.36	2.4	1.5	4.26	0.4	3.3	7.56	56.3	8.6
Good	6.6	7	0.67	4.4	1.3	6.37	0.1	1.3	7.67	83.1	1.6

Sources: Soil samples were collected and analyzed by Angelo Mansur and Tarcizio Ewerton Rodrigues. Tâmara Gomes and Chantal Line Carpentier generated soil quality categories. N = 61.

Notes: This table of soil characteristics should not be viewed as static or as being independent of land use. Soil characteristics change over time, especially when land is converted from forest to agriculture; hence, the values of the soil characteristics noted here and others (especially those related to soil physical properties) will in part depend on the land use history of sampled plots. pH refers to the level of acidity (neutral range = 6.6 to 7.3); P refers to levels of available phosphorus in soils (average range = 11 to 30 mg/dm³); K refers to levels of available potassium in soils (average range = 0.13 to 0.38 Cmole/dm³); Ca is calcium; Mg is magnesium (average range for Ca + Mg, = 2.1 to 6.0 Cmole/dm³); S is the sum of Ca, Mg and K (average range = 2.6 to 5.5 Cmole/dm³); Al is aluminum (toxicity begins at about 0.3 Cmole/dm³); H + Al measures potential acidity; T measures the sum of cation exchange in soils (T = S + H + Al, moderate range = 5.1 to 15.0 Cmole/dm³); V measures base saturation (V=(100 S)/T, average range = 51 to 70); and m measures aluminum saturation (levels above 50 percent can cause production problems).

⁵²Soil samples were taken from land under different uses (such as forest, annual crops, perennial tree crops, and pastures), but priority in the analysis of soil samples was given to samples taken from pastures and forests. The soil quality categories presented here were derived on the basis of the results of the analysis of this priority subset.

labor costs to control weed growth. The model weighs these financial considerations in determining product mix and production technology (and implicitly the use of purchased inputs). Unless otherwise stated, simulations assume medium-quality soils throughout the farm; implications for results of soil quality differences are explored in the section on sensitivity analysis.

Translating Soil Quality Indicators into Yield Coefficients

Interviews with farmers located on soils where soil testing was done (or located on soils judged by soil scientists to be similar to those), combined with expert interviews with extension agents and scientists were used to estimate crop- and technology-specific yield coefficients for each of the three qualities of soils prevalent in the sample. The model specifies three types of technologies for most products: V1 being the most rudimentary technology, with no purchased inputs used; V2 being a more advanced technology, using some purchased inputs; and V3 being the most advanced and using relatively large amounts of purchased inputs. All technologies have constant returns to scale, and there is no substitution among inputs for a given technology (although expanding the range of fixed-coefficient technologies available to the farmer for a given product does permit a kind of substitution). Table 4.3 identifies crops included in the model and reports the yield coefficients estimated for each product-technology-soil combination by this participatory assessment of the impact of soil quality on *peak-year* crop yields using different production techniques.⁵³

The peak-year yields reported in Table 4.3 can vary over time for given plots of

land, except those associated with V3 technologies, which (by design) correct soil chemical imbalances prior to planting and annually replenish soil nutrients depleted during production. The most commonly encountered production technologies in the field (V1 and V2 technologies) all experience yield declines when practiced on the same plots over time, and these yield declines were measured for inclusion in the model. Figure 4.2 depicts yield declines as a result of nutrient deficiencies, for a rotation involving intercropped rice and corn followed by beans, using (low-level) V1 production technology. With no external inputs, yields for this technology drop to zero after year two for rice and beans and after year three for corn. Similar yield drop-off patterns occur for V2 technologies, but first-year yields are higher for these more intensive cropping systems. Yield drop-off rates are similar for given product-technology combinations across all soil categories (based on the field experience of soil scientists, with acknowledgment that data were lacking to substantiate this).

For pasture, farmers may choose the area's most prevalent planted pasture (*brizantão*) alone, with two different levels of herd management techniques (V1 and V2). V2 involves more extensive health care, separation from herd of lactating calves and their mothers, and pasture rotation. The other option is *brizantão* in association with the nitrogen-fixing species kudzu (*pueraria*) (which requires V2 management techniques). Figure 4.3 documents seasonal gaps in carrying capacity for the pasture management combinations, as well as the earlier drop-off in carrying capacity associated with the pasture-alone system versus the pasture-with-kudzu

⁵³Peak yields for annual crops occur during the first year of planting; these first-year estimates are used to compare yield effects across soil quality categories. However, annual crops produced using V1 and V2 technologies experience significant, and different, yield declines over time. This issue is examined in some detail below for annual crops, and it is also taken up in a footnote to Table 4.3.

Table 4.3 First-year crop yields, by technology level and by soil quality

Crop/soil quality	Monoculture ^a			Intereropped ^b	
	V1	V2 ^c	V3 ^d	V1	V2
Rice (kilograms/hectare)					
Poor	...	1,500	3,400	620	488
Medium	...	2,000	3,400	799	1,300
Good	...	2,500	3,400	992	1,642
Corn (kilograms/hectare)					
Poor	...	2,000	3,500	488	800
Medium	...	2,500	3,500	640	900
Good	...	3,000	3,500	800	1,000
Beans (kilograms/hectare)					
Poor	...	500	1,500	202	500
Medium	...	800	1,500	390	800
Good	...	1,000	1,500	565	1,000
Manioc ^e (tons /hectare)					
Poor	17	17	...	...	...
Medium	19	19	...	...	...
Good	22	22	...	...	...
Coffee ^f (kilograms/hectare)					
Poor	500	...	3,500	...	...
Medium	970	...	3,500	...	...
Good	1,200	...	3,500	...	...
Bananas (bunches/hectare)					
Poor	800	...	1,300	...	...
Medium	800	...	1,300	...	...
Good	800	...	1,300	...	...

Sources: Productivity parameters were generated on the basis of meetings with farmers' groups, extension agents, and agricultural researchers. V1 intercropped parameters were first estimated from field data and then verified by meeting participants.

^aV1 annual food crop monocultural technologies are neither practiced by small-scale agriculturalists in the sample area nor selected in the model simulation and have been omitted from the table.

^bV3 intercropping technologies are not practiced by small-scale agriculturalists, nor is their development contemplated by agricultural researchers; therefore they do not appear in the table.

^cV2 monocultural and intercropping technologies make use of some pesticides, primarily insecticides, but do not use chemical fertilizers.

^dV3 monocultural technologies make use of both pesticides and chemical fertilizers, adjusting use of the latter to compensate for inherent differences in soil quality; hence, V3 technology yields do not vary across soil quality categories.

^eManioc yields are identical for V1 and V2 technologies.

^fYields for coffee and bananas begin low, increase over time, and then drop off, and the yield drop-offs are much quicker for V1 technologies than for V3 technologies. Yield figures for coffee and bananas represent peak yields achieved for these crops (plateau yields for V3 technologies, over the productive life of the plant); yield peaks/plateaus are achieved for V1 coffee in year three, for V3 coffee in year four, for V1 bananas in year three, and for V3 bananas in year four. During the establishment phase, coffee is often intercropped with rice and beans; mature coffee is generally cultivated as a monoculture.

Figure 4.2 Yields for intercropped annual crops, using V1 technology

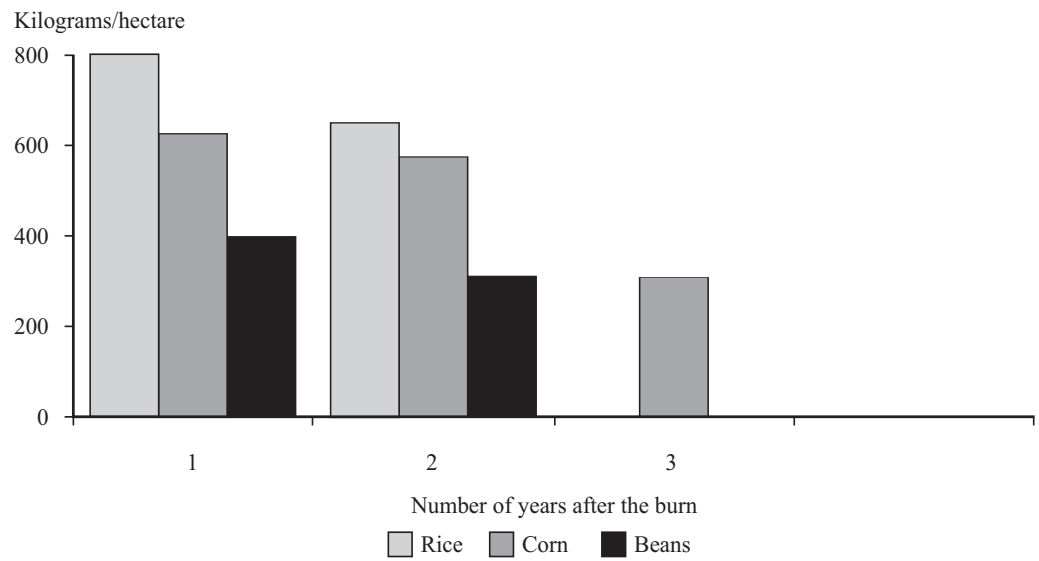
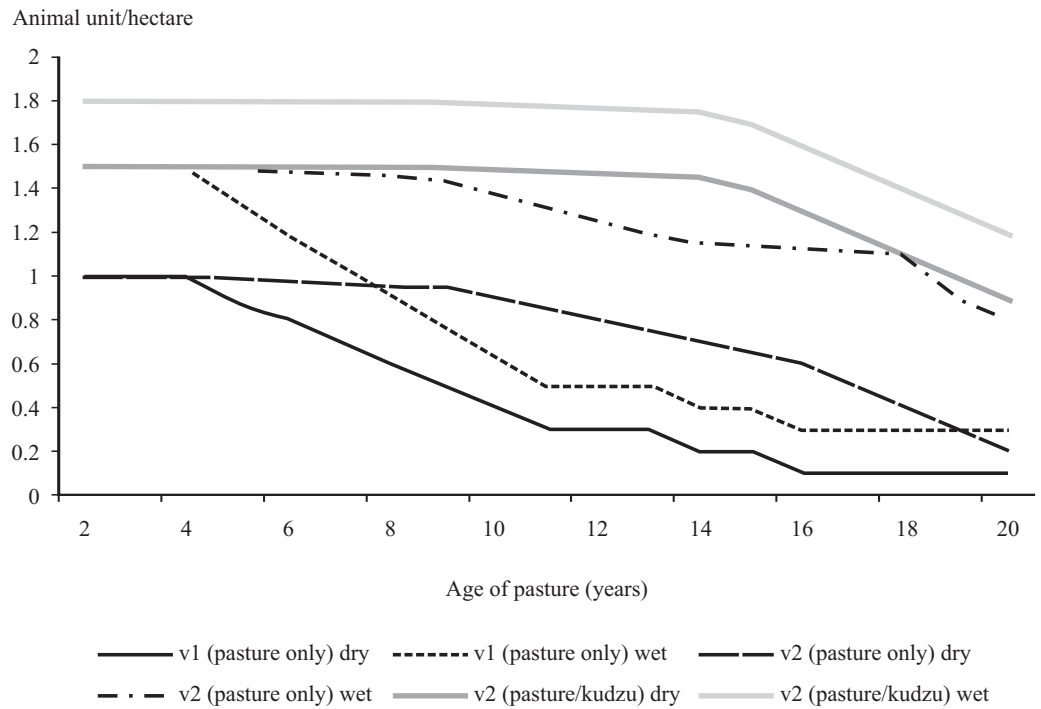


Figure 4.3 Seasonal pasture carrying capacity under V1 and V2 management



system. Declines occur even earlier when herd management on pasture alone is at the lowest (traditional) level. The drop-offs indicate that, given other conditions, these carrying capacity levels constitute overgrazing (the degree of overgrazing built into technology choice and the number of options is based on farm interviews, so the amount of overgrazing is not a freely chosen variable in each year for the farmer). For more detail on these pasture systems, see Vosti et al. (2001a).

The model also includes soil nutrient recovery rates, allowing tree-based fallows to recover a fixed proportion of lost nutrients each year, achieving complete recovery (nutrient level commensurate with forest) after five years. These nutrients are available for agriculture if the fallow is cleared and burned.

Market- and Policy-Related Site Characteristics

In addition to capturing market prices for inputs and outputs from the farm perspective, the model limits certain input and product flows on and off farms to reflect market imperfections. Except where restrictions are explicitly lifted, they apply to all the simulations presented. While the model assumes that all output is potentially marketable, quotas, imposed by processors at the time of the survey, reflect marketing bottlenecks that still persist on the research site. Quotas constrain milk sales to 50 liters per day. Hired labor that can be acquired in any given month is limited to 15 person-

days, reflecting labor scarcity in the area. The only credit in the model is borrowing to meet seasonal subsistence needs, in keeping with survey responses regarding access to credit (as opposed to prevalence of loans). The model includes some forestry policies but excludes others to reflect the policy setting in the western Brazilian Amazon regarding the degree to which forest areas are available for economic activity. For example, in the model, small-scale farmers are not allowed to harvest timber products from their forested land.⁵⁴ In addition, a 50 percent rule mandating that no more than half of any farm be cleared for agricultural purposes is not enforced in the model simulations presented here, except those simulations addressing this specific policy issue.⁵⁵

Model Baseline: A Test of the Sustainability of Small-Scale Agriculture at the Forest Margin

The farm-level bioeconomic model can track resource use strategies adopted by the archetypical household over a 25-year time horizon using a whole-farm perspective, given household choices among many possible activities at several different levels of technology and mimicking the constraints they face. The results of baseline model simulations are compared with field data on land use and forest retention for a cross section of farms of different “ages,” beginning with those opened around 13 years prior to the study (the archetypical farm’s point of

⁵⁴Although technically permissible by law, the bureaucratic obstacles to obtaining official permission to sustainably harvest timber products in farmers’ legal reserves have been, in practice, insurmountable, and have indeed made any on-farm timber extraction difficult. Recent changes in certification requirements may, in the future, reduce these costs.

⁵⁵The federal law obligating landowners to retain 50 percent of their holdings as forest reserves (*reservas legais*) and to obtain deforestation permits for all forest felling is Law Number 4.771, dated September 15, 1965, of the *Código Florestal Brasileiro*. This law was modified in 1997 by a presidential decree, which stipulated that in states lacking approved zoning plans, farms must retain 80 percent of their land in primary forest. Small-scale farms were eventually exempted from this decree, but a more recent decree removed the exception. In practice, many farmers retain less than 50 percent (or 80 percent) of their private forest reserves, and fines are rarely assessed on smallholders.

departure). The progression of predicted uses of cleared land and the amount of forest retained on the archetypical farm in any given year of the 25-year simulation did not deviate substantially from average patterns observed on sample farms of comparable age and size, but the progression was slightly more rapid.⁵⁶ This jibes with expectations that including risk and accounting for farm turnover, particularly at the onset of the settlement period, would slow deforestation rates from those modeled here. The effect of including off-farm investments outside agriculture on modeled deforestation rates is ambiguous over the time horizon in question, however. It would take pressure off the forest by diverting resources out of the agricultural sector in the shorter term, but the returns could be reinvested in the agricultural sector if this were more profitable, accelerating deforestation. The effects of risk and investment assumptions are discussed more fully in the section on model assumptions and their implications.

This discussion focuses on three sets of indicators: land uses (implicitly including deforestation) and economic activities, labor uses, and farm profits.⁵⁷

Figure 4.4 depicts the land uses generated by the model for a 25-year time span under baseline conditions (a well-situated farmer with medium-quality soils under the market and policy setting for Pedro Peixoto,

Acre). Several results emerge from this baseline. The amount of forest retained is clearly declining over time, finally disappearing in about year 25, despite the small but positive revenue provided by the extraction of Brazil nuts (an activity currently undertaken by about half of sample farms). In terms of area, cattle production is the dominant activity, and pasture to support it, mostly *brizantão* combined with kudzu, eventually occupies about 85 percent of the farm. Annual crop production occupies about 8 percent of the farm throughout the 25-year time horizon, with V1 (lower technology) systems of intercropped rice and corn coexisting with V2 (higher technology) rice alone. The farmer does not choose to grow any perennial tree crops (coffee and banana are options)—only manioc (classified in the model and figure as a perennial because its production cycle spans more than one year). Manioc takes up about a hectare of land over time, and secondary fallow weaves into and out of the baseline land use scenario, becoming significant as forests disappear completely.

The dominance of pasture on the archetypical farm merits a closer look. Figure 4.5 depicts three types of cattle (milk cows and beef cattle in animal units (AU), and calves), and the total pasture available for maintaining the herd at different points in time.⁵⁸ The model replicates the dual dairy–beef operations prevalent in the

⁵⁶The model is also validated by testing its stability to changes in prices and other parameters and comparing shadow prices on constraints to prices in the model. Some of these validation results appear later in this chapter as policy simulations or are referred to in the discussion in the section on model sensitivity to changes in parameters.

⁵⁷This section on baseline results contains figures and discussions (for example, labor hired in and cattle herd dynamics) that, to save space, are not replicated in sections on model stability or policy experiments. In addition to information presented here on farm profits, the model generates output on savings and consumption (the element maximized in the model). The model also generates information on yearly total crops produced, consumed, kept in stock and sold; grains and beans bought for consumption and to use as seeds; nitrogen in cultivated and forested areas; equipment stock and purchases; and transportation means and months to bring crop sold to the market. For details, see Appendix B.

⁵⁸The conversion of “heads” to animal units (AU) is as follows: calf = 0.25 AU, heifer = 0.5 AU, cow = 1.0 AU, bull = 1.25 AU, and an ox = 1.5 AU (EMATER and Embrapa 1980). The bioeconomic model does not allow overgrazing, but underutilization of pasture is permitted.

Figure 4.4 Land uses, baseline scenario

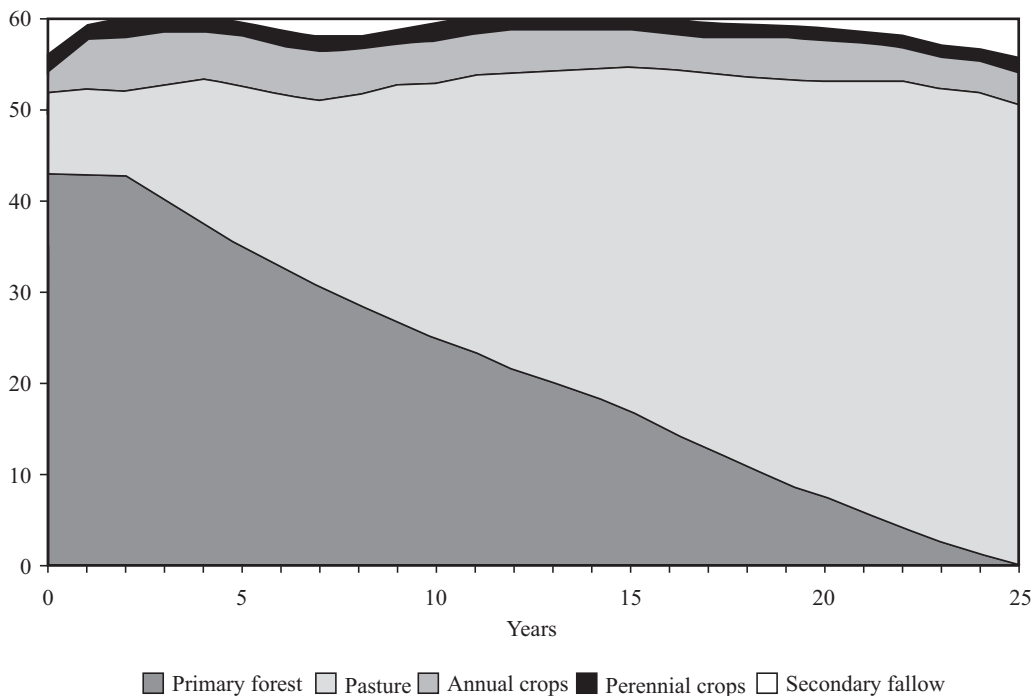
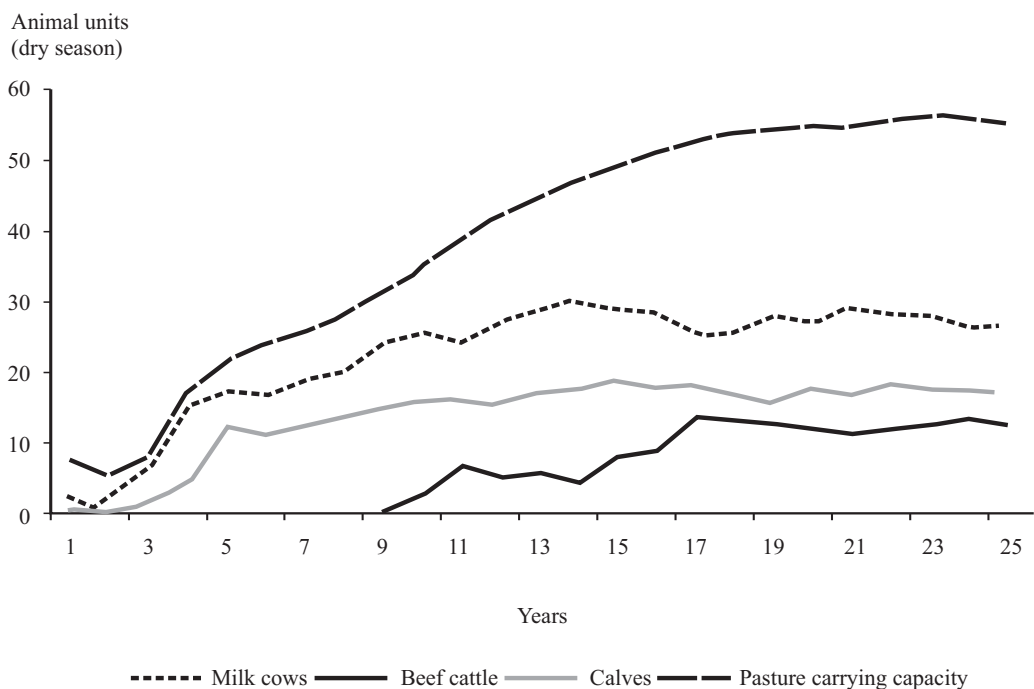


Figure 4.5 Cattle herd dynamics and pasture carrying capacity, baseline scenario

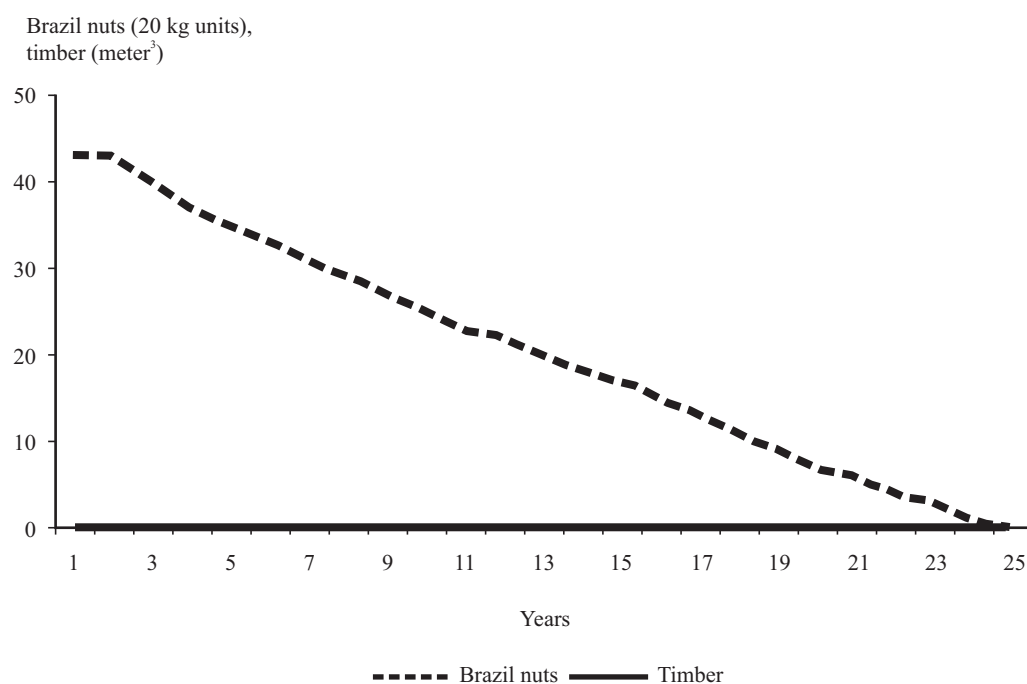


sample. Dairy production begins early in the 25-year scenario and plays an important role throughout. Once the milking herd is established (say, by year 10) roughly 77 percent of income is derived from dairy operations. These dairy operations occupy an average of 42 percent of available household labor in each month except May, when pasture and animal care account for 128 percent of available household labor, implying that 15 person-days (the maximum allowed by the model) must be hired in. Beef cattle production emerges in year 9, and its contribution to income peaks in year 18, at which time it represents 25 percent of household income but on average occupies just 4 percent of available household labor each month.

Extractive activities are a constant but diminishing source of income to smallholders in the baseline run.⁵⁹ Figure 4.6 depicts this steady decline in extractive activities.

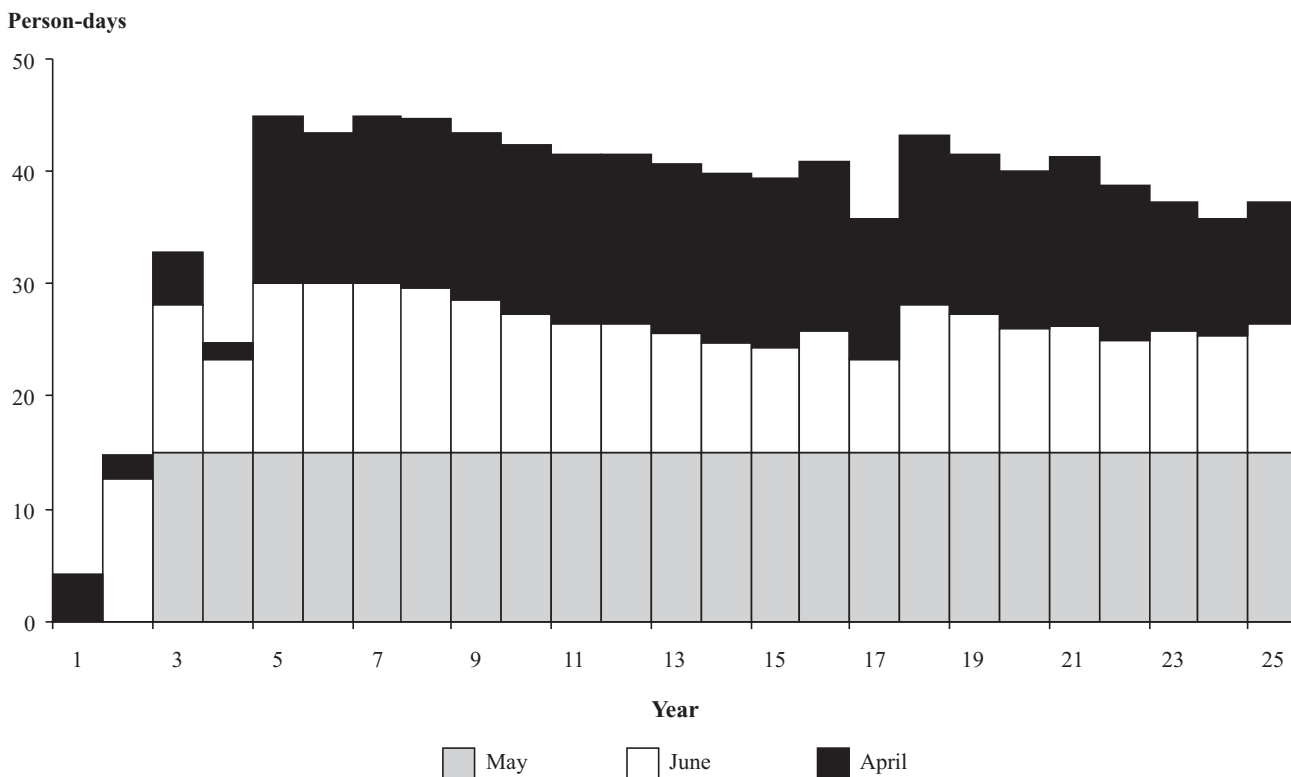
Labor emerges as a critical determinant of land use and deforestation. An unlimited labor supply at 1994 wage rates would mean a quick and complete deforestation. The constraint on hiring in or out more than 15 person-days per month shows that labor markets are not perfect in these remote areas. Labor can be hired in and hired out simultaneously in a given month. Only adult male labor can be hired in or out, and some tasks can only be performed by adult males. Households generally cannot hire as much labor as they want and can afford (the labor constraint frequently binds). Figures

Figure 4.6 Extractive activities on small-scale farms, baseline scenario



⁵⁹The supply of Brazil nuts is directly linked to the amount of forest cover remaining on farms. The same survey data from 1994 used to identify farm types were also used to estimate Brazil nut off-take.

Figure 4.7 Labor hired in, by month, baseline scenario



Note : April, May, and June are the only months when labor is hired in.

4.7 and 4.8 depict monthly labor purchases and sales, respectively, by month, for the 25-year baseline scenario. Labor purchases in May for deforestation, fence construction, and maintenance almost always reach the established limit. Labor purchases in February and in April for annual crop production often reach the 15 person-days per month limit, too.

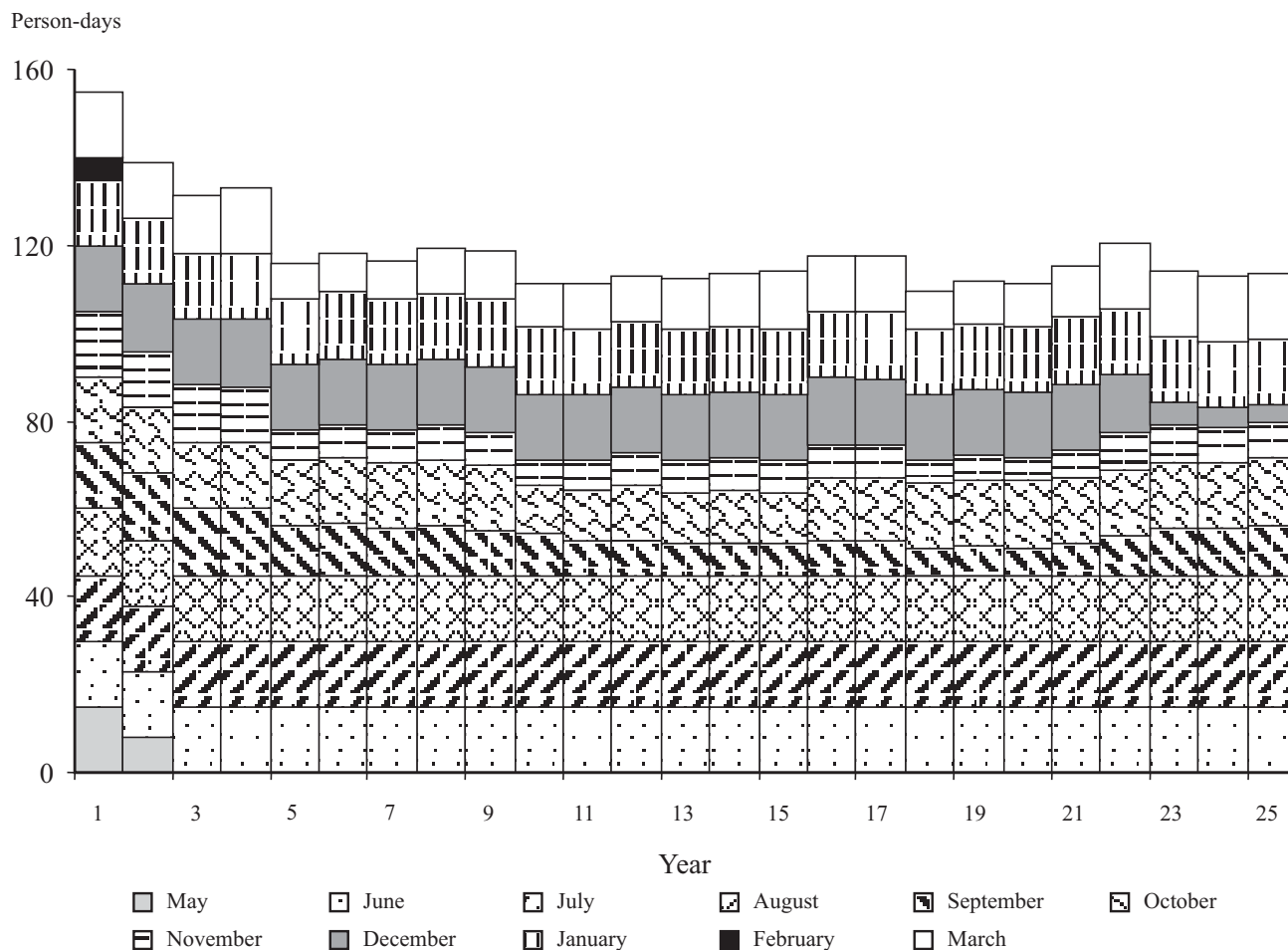
The model suggests that households will generally take maximum advantage of off-farm labor opportunities, almost regard-

less of season.⁶⁰ Indeed, as Figure 4.8 suggests, during June, July, and August, the household sells as much labor as it is allowed. Labor is seldom sold off-farm in February, April, or May, and depending on the year of the simulation period, some labor is sold in the remaining months, but not up to the established limit.

Figure 4.9 depicts monthly labor use on the farm (again, measured in person-days for both hired and family labor) by class of activity, for year 10 in the 25-year baseline

⁶⁰Wages vary seasonally in the model: during peak season months (May and June), the daily wage is R\$7.00 per day; in relatively high demand labor months (March and April), the wage is R\$5.60 per day, and the wage for off-peak months is R\$3.70 per day. When the farm household hires labor, a 12.5 percent wedge per day is added to the wage to reflect supervisory costs.

Figure 4.8 Family labor hired out, by month, baseline scenario



scenario. Labor use patterns vary over the 25-year baseline scenario, but the important elements of these patterns are captured in the figure for year 10.

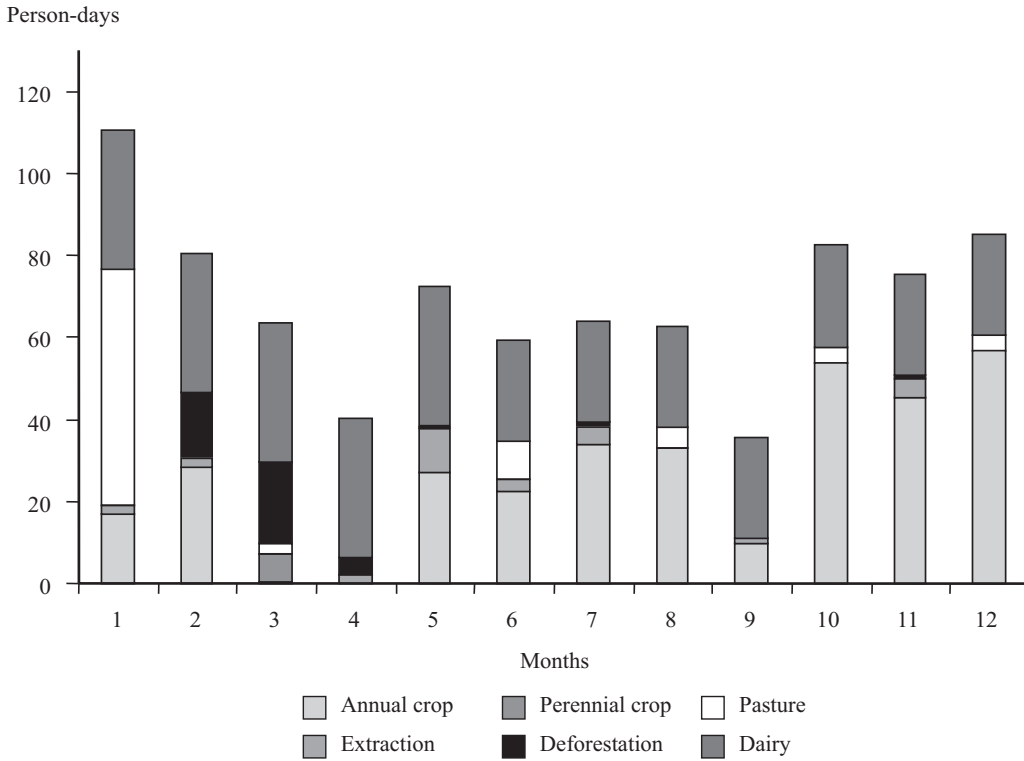
This figure reflects the agricultural calendar for the products selected in the model (month 1 is May). Dairy and livestock activities take up fairly constant proportions of household and hired labor. Pasture establishment takes place in December (month 8 in Figure 4.9), with maintenance activities spread through October (6), February (10), April (12), and especially May. Deforestation takes place primarily in June and July (2 and 3). Annual cropping activities absorb some labor in all months except July and August, with intensive use in Feb-

ruary, March, and April, the harvest months.

The model generates several measures of financial returns for each simulation. Figure 4.10 depicts the net value of total output, by source, for each year. Dairy and livestock activities contribute most to this measure of income beginning in about year 4, with annual crops next but much lower in importance. Net labor receipts (value of labor sold minus the value of labor hired in) contribute a fairly important share during the first couple of years and remain constant (but small) thereafter.

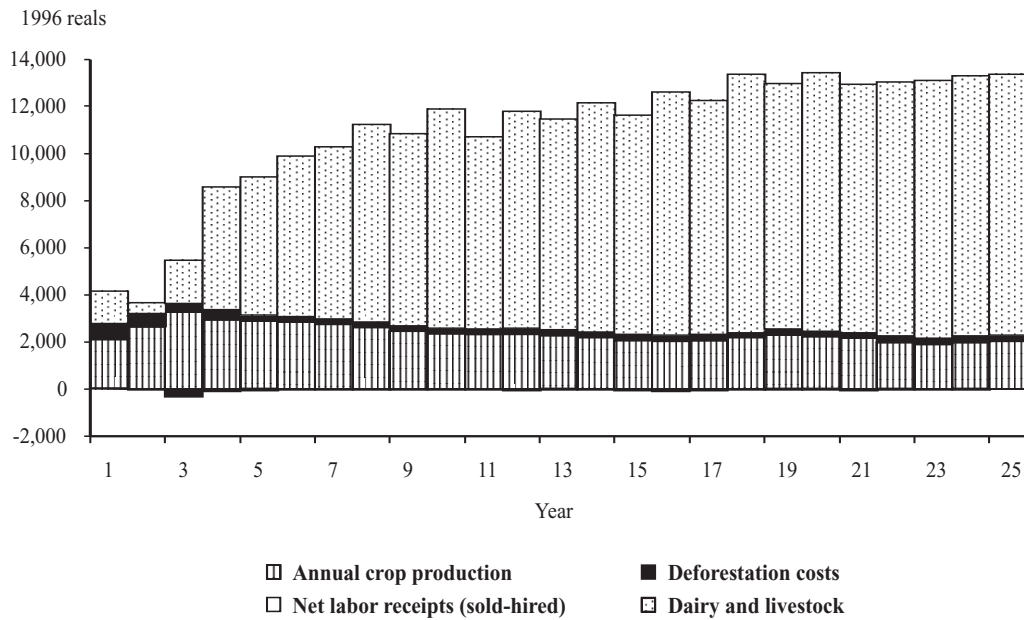
Figure 4.11 depicts farm profits (consumption plus savings; the latter can be negative). Profits are net of the cash value

Figure 4.9 Labor use, by activity and month, for year 10 of the 25 year baseline scenario



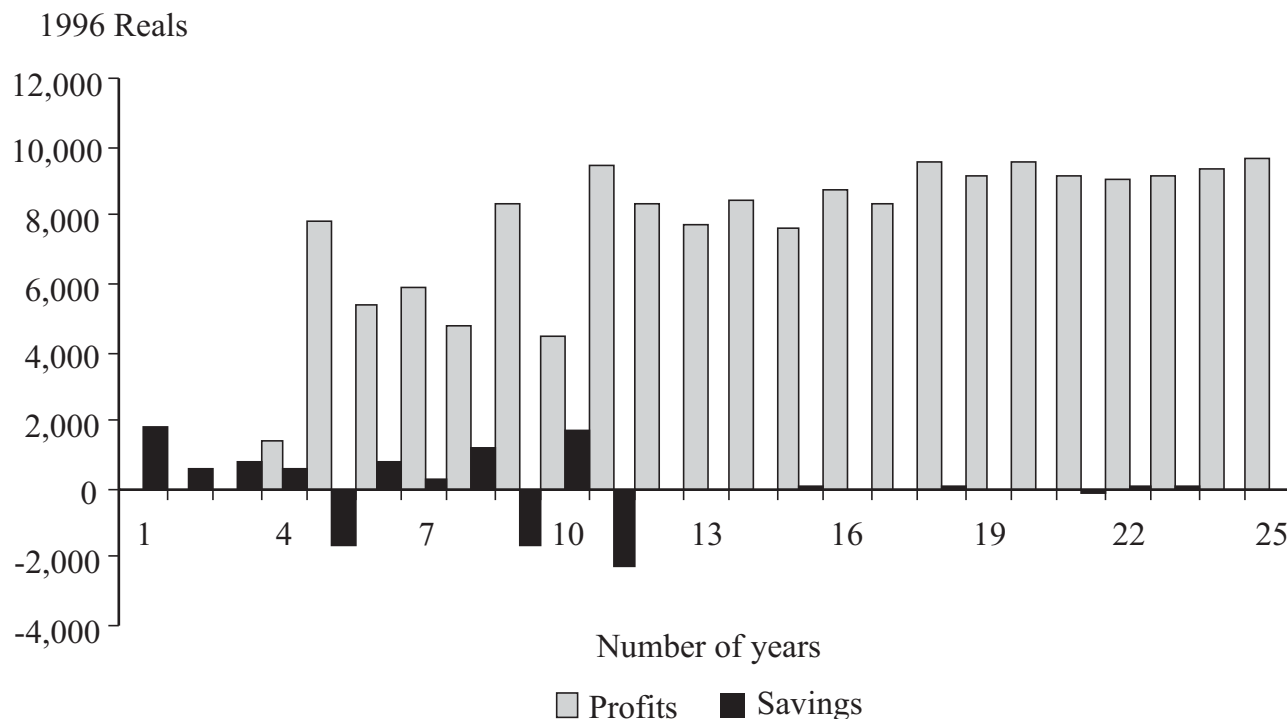
Note : Month 1 is May and month 12 is April.

Figure 4.10 Net value of total output by source, baseline scenario



Note : Net value is the value of total output minus variable costs.

Figure 4.11 Farm profits and savings by year, baseline scenario



of basic food needs and cash required for minimal living expenses, with minimum consumption in the model determined by regional food habits and household size.⁶¹ Savings during the first few years allow for subsequent investments that boost consumption in later years. Large investments (negative savings) are required in years 5, 9,

and 11 to expand pasture areas. Nominal profits plateau at about year 13, at a level of approximately R\$9,000.⁶² The net present value of the 25-year profit stream is R\$50,635 (at a 9 percent discount rate), yielding an annuity value of R\$2,025 (R\$50,635 divided by 25, the number of years in the simulation).⁶³

⁶¹Farm households were asked how much they spent per month on fixed expenditures such as sugar, salt, cooking oil, clothes, and hoes. Households are required to have on hand sufficient food (either in-kind or in cash to purchase it) to feed family members each season (seasons were six months long, one rainy and one dry). Borrowing (that is, negative savings) to meet consumption needs is allowed, but must be repaid by the end of the calendar year in which the loan is taken out.

⁶²This figure and the rest in this report are in 1996 prices, when the Brazilian real (R\$) was worth about US\$1.00 (World Bank 1997).

⁶³The 9 percent discount rate was selected in consultation with local researchers and farmers and does not reflect variation among smallholders in cost of capital due to varying circumstances and access to credit. The sensitivity analysis, however, reveals that land use patterns seen in the baseline were robust across a range of discount rates.

For an average family (mean size 5.6 people), these financial benefits amount to an annual value of R\$1,619 per capita (undiscounted) once profits hit their plateau, and approximately R\$364 per capita (discounted) per year smoothed over the 25-year horizon (based on the above annuity value). Although the model contains simplifying assumptions that make comparisons with profits from other sources subject to caveats,⁶⁴ this annuity figure falls considerably below the Brazilian 1995 per capita GDP of approximately R\$3,640, but above a World Bank (1997) estimate of its poverty line, R\$269 per person (Faminow et al. 1999). Financial incentives could thus exist for the poorest in Brazil to migrate to the area to establish small-scale agricultural enterprises (but costs of migration, reestablishment, and risk associated with migration and subsequent agricultural activities would have to be fully assessed to verify this).

The baseline suggests that the farming systems characterized by the model facing prices and technologies reflecting conditions on the ground at the time of the 1994 survey will result in complete deforestation in about 25 years.⁶⁵ This archetypical farm would thus fail any test of sustainability that requires that some area remain in primary forest but pass aspects related to sustaining livelihoods, demonstrated by the increased and sustained flows of income generated by combinations of agricultural, extractive, and off-farm activities over the model's time horizon.

Responses to Changes in Factor Endowments and Critical Model Constraints

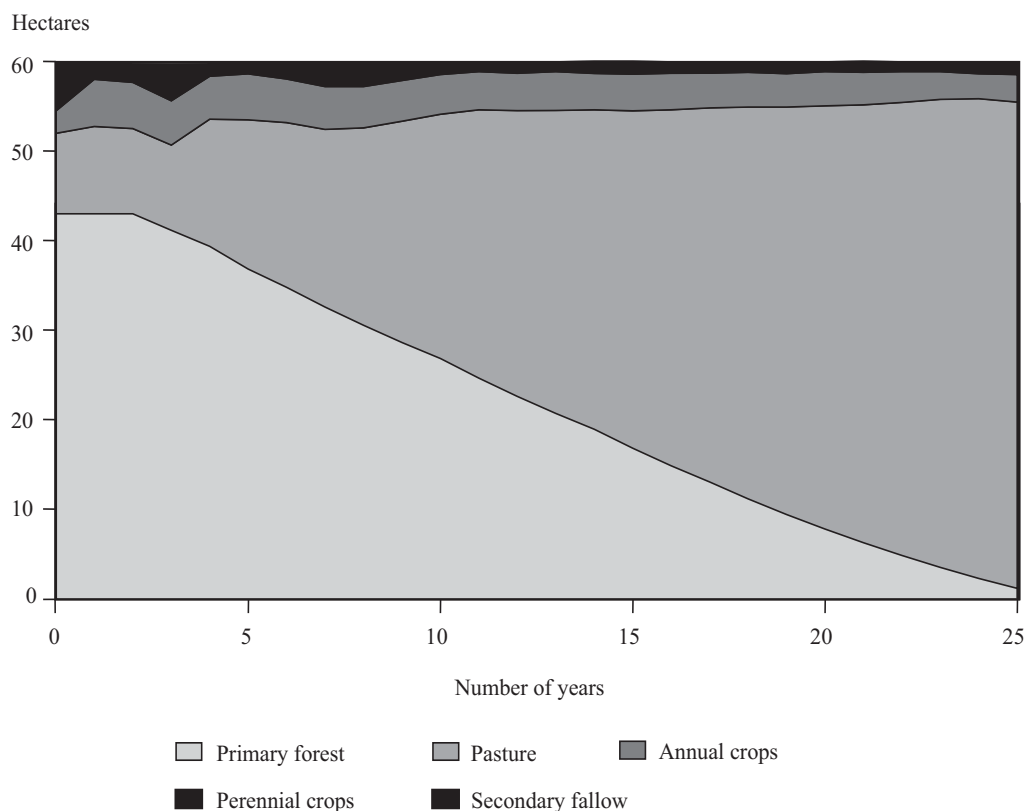
The model is tested for sensitivity to changes in key parameters, including those known to vary by farm household (for example, soil type and farm-gate prices) or those that represent one reflection of local market conditions (for example, constraints on the volume of monthly labor flows or the discount rate).

Sensitivity to Labor Constraints and the Discount Rate

The model is extremely sensitive to changes in the amount of labor that can flow onto farms. Unlimited supplies of labor, even at a relatively high market wage rate in 1994 (R\$7.00 per person-day), translate into rapid rates of deforestation. Sensitivity analysis indicates, however, that deforestation rates and patterns of use of cleared land did not change even with sizeable changes in the discount rate (up to 21 percent) because the biophysical and other constraints in the model severely limit land use and technology options. This situation captures the gist of the situation for the real life counterpart of the archetypical farmer seeking to meet food security needs and maximize profits, who has little latitude in selecting land use patterns or changing established ones in response to a drastically higher discount rate. As the section on model assumptions discusses, farmers

⁶⁴The baseline profits may fall in the upper range of likely conditions on the ground that the model does not account for risk and does not incorporate results for farmers less well situated vis-à-vis markets (described in Carpentier, Vosti, and Witcover 1999). Additional profit could come, however, from realistic off-farm investment opportunities (not currently an option in the model). The model simulations presented below do not explicitly involve changes in these dimensions vis-à-vis baseline conditions. Results can be compared across scenarios with the caveat that some bias may be introduced to the extent that assumptions affect scenarios differentially. These topics are discussed in the section on model assumptions and their implications.

⁶⁵Recall that this rate of deforestation may be an upper bound because of model assumptions regarding risk and farmer turnover, plus the fact that the model depicts only farmers who are well situated vis-à-vis markets (roughly half of the sample).

Figure 4.12 Land uses with poor-quality soils

nevertheless have more choice than a simplified model can reflect.

Sensitivity to Soil Quality

The bioeconomic model is run using the crop yield coefficients for the other levels of soil quality. Figure 4.12 presents aggregate land use categories (and implicit deforestation patterns) for small-scale farms located on *poor* soils with generally *lower* yields.⁶⁶ Compared with the baseline (medium-quality soils and land uses depicted in Figure 4.4), deforestation is only slightly slower, especially after year 10, resulting in a small patch (about 1 hectare) of primary forest remaining in year 25 (the

baseline had no primary forest at that point). The farm with poor-quality soils dedicated even more land to pasture and less to annual crop production and secondary fallow than in the baseline run, and it did not resort to application of chemical fertilizer. The farm with poor soil quality had a net present value of profit over the 25-year simulation time horizon of R\$44,132, about 15 percent lower than the R\$50,635 earned under the medium-quality soil of the baseline scenario.

Figure 4.13 presents aggregate land use categories and deforestation patterns for small-scale farms located on good soils with generally *higher* yields. Deforestation

⁶⁶Initial runs of the model for poor soils yielded infeasible solutions, probably due to the inability of smallholders to feed their families adequately, which the model requires. Small amounts of additional cash had to be “added” to the initial conditions for the poor-quality soil runs to avoid this problem.

is still slower than in the baseline scenario, although almost negligibly so, about 3 hectares of primary forest remaining in year 25 (versus zero for the baseline at that point). Regarding use of cleared land, the farm with good-quality soils has slightly more area dedicated to annual crop production than the baseline, and makes slightly greater use of secondary fallow. The net present value of profit over the 25-year simulation time horizon for the good-quality soils simulation is R\$60,478, or about 20 percent higher than the R\$50,635 earned under the baseline scenario.

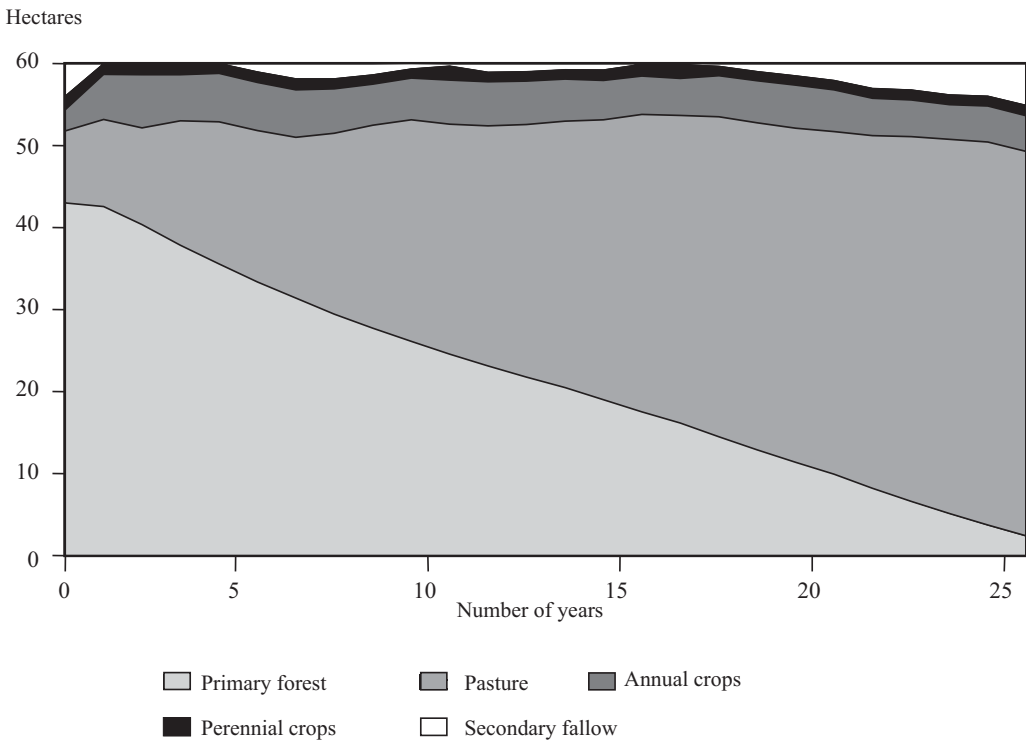
Deforestation patterns are therefore similar for both good and poor land, but with substantial income differences: a farm with good-quality soil can generate about 35 percent more income than one with poor-quality soil. Regardless of soil qual-

ity, the forest disappears within a period of 25–30 years, with farmers with good-quality soils deforesting only slightly more slowly than those with poor-quality soils. Both scenarios continue to be dominated by pasture, but good soils lead to greater amounts of annual crop production and to the use of more secondary fallow than do production systems on poor soils. Neither the farmers with more severe soil fertility problems, nor those with relatively good soils, where yields could still benefit from soil amendments, opted to purchase and apply chemical fertilizers.

Sensitivity to Price Changes

Variations in prices can affect deforestation and especially the use of cleared land (Barrett 1999).⁶⁷ Table 4.4 presents changes in market prices for important agricultural

Figure 4.13 Land uses with good-quality soils



⁶⁷See Dahl (1998) for details of price trends and volatility for major agricultural products in the Acre study site.

products and inputs over the sample period 1994–96. A baseline simulation (with medium-quality soils and 1996 prices) is run to assess the impact of some fairly dramatic changes in relative prices since 1994,

especially for coffee (a 411 percent increase) and labor (a 43 percent increase).⁶⁸ Figure 4.14 depicts land uses for a 25-year simulation using 1996 rather than 1994 prices. Deforestation rates are substantially

Table 4.4 Farmgate prices, 1994 and 1996

Commodity/input	Price per	Farmgate prices (1996 R\$)		Change (%) 1994–96
		1994	1996	
Commodity				
Rice	Kilogram	0.27	0.20	-26
Corn	Kilogram	0.15	0.17	13
Beans	Kilogram	0.51	0.52	2
Coffee	Kilogram	0.28	1.43	411
Brazil nuts	18 kilograms	2.60	3.20	23
Bananas	Bunch	0.87	1.94	123
Timber	Meter ³	110.00	120.00	9
Calves ^a	Head	102.00	134.00	31
Cows ^a	Head	210.00	290.00	38
Beef ^a	Head	350.00	364.00	4
Milk ^b	Liter	0.36	0.40	11
Input				
Rice seed	Kilogram	1.74	1.80	3
Corn seed	Kilogram	1.72	2.40	40
Bean seed	Kilogram	2.27	2.40	6
Coffee seedlings	Each	1.00	0.30	-70
Grass seed ^c	Kilogram	2.36	2.36	0
Kudzu seed ^c	Kilogram	11.60	10.00	-14
Sacks	Each	0.85	0.65	-24
Pesticides (weed and insect)	Kilogram	24.00	21.60	-10
Nitrogen fertilizer ^d	Kilogram	1.21	1.08	-10
Chainsaw	Purchase price	1,441.00	841.00	-42
Oxen and cart	Purchase price	1,525.00	1,120.00	-27
Chainsaw rental rate	Rental and operator	37.00	50.00	35
Fence cost ^a	Kilometer	302.00	307.00	2
Animal care ^a	Per animal unit	5.18	4.14	-20
Wage rate	June	7.00	10.00	43
Bull ^a	Purchase price	823.00	823.00	0
Timber transport	Meter ³	15.00	10.00	-33
Truck rental	Trip to market	91.00	91.00	0

Sources: The price vector labeled 1994 is the vector of prices judged to influence 1994 land uses and reflects market prices for the agricultural year 1992/93. Likewise, 1996 prices represent market prices for the 1994/95 agricultural year. This terminology is used throughout this section. All prices reflect values for average-quality products and inputs for that region; regional product quality is not high by national standards, especially for coffee.

^aV1 technology.

^bAll technologies.

^cV2 technology.

^dV3 technology.

⁶⁸Note that livestock product prices rose, but not so dramatically, and the price of one key annual crop dropped substantially, while prices for inputs other than labor dropped, except for annual crop seeds.

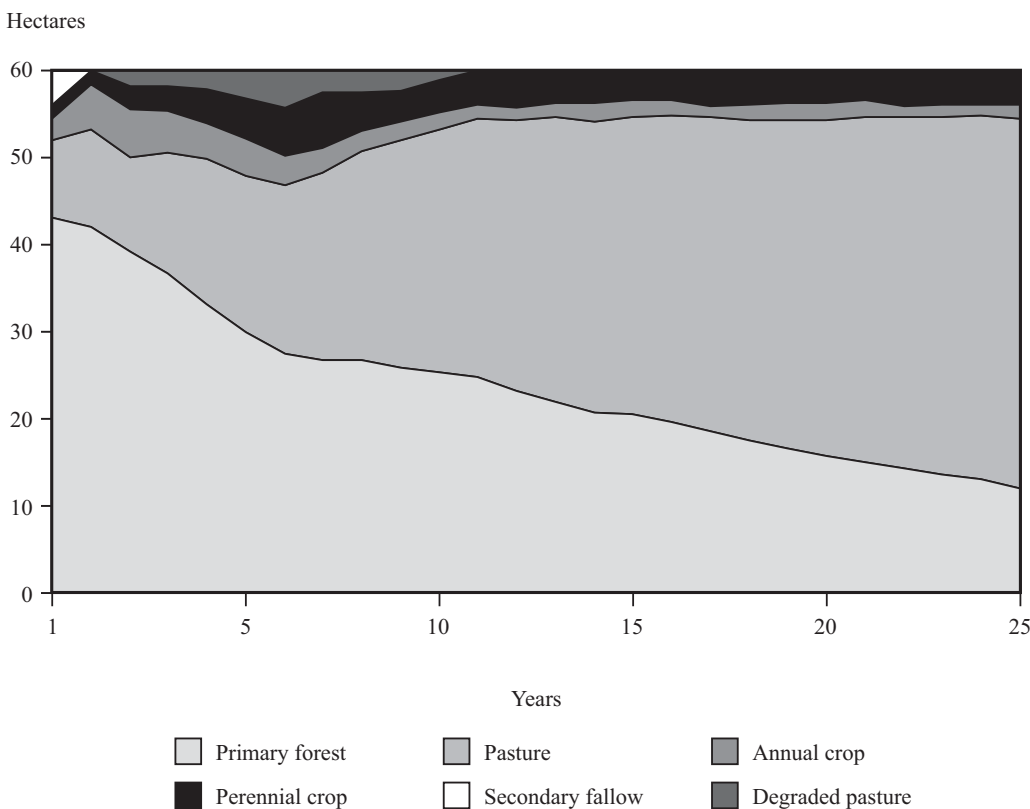
reduced largely because family and hired labor are reallocated to establish and maintain coffee plants.⁶⁹ The impact of increased labor requirements for coffee (primarily during harvesting) is reflected in the rapid decline in deforestation after about year 7, when the substantial coffee area established during years 1 to 6 comes into full production. Still, at year 25, forest is still declining and pasture increasing its area, while area allocated to annuals and perennials remains somewhat stable. Under the 1996 price scenario, farm income increases substantially, to R\$80,719 (from the 1994 price baseline NPV of R\$50,635).

Table 4.5 summarizes the general effects of changes in key model parameters and initial conditions on three important outputs—deforestation, use of cleared land, and household income.

Technology and Policy Experiments Using the Model

This section reports results of several policy experiments run using the bioeconomic farm model. In each case, one or more important model parameters or constraints are modified for the entire 25-year simulation period. Experiments are designed to address key policy issues in the western

Figure 4.14 Land uses, baseline simulations using 1996 prices



⁶⁹Note that increased wage rates under this scenario raise costs of forest felling as well as costs of production on cleared land, but the farmer is still limited by the hired labor constraint during the year.

Table 4.5 Summary of sensitivity analysis for the linear programming model

Variable	Does this variable affect		
	Deforestation	Use of cleared land	Income
Soil quality	No	No	Yes
Labor availability	Yes	No	Yes
Prices	No	Yes	Yes
Discount rate	No	No	No
Distance to market	Yes	No	Yes
Market access	Yes	Yes	Yes

Brazilian Amazon, specifically (1) effective implementation of the 50 percent rule, (2) direct payments to smallholders for retaining forest, (3) permitting small-scale managed forestry, (4) a complete absence of technological change in agriculture, (5) fertilizer subsidies, and (6) a multiple-policy scenario simultaneously permitting small-scale managed forestry and offering a 50 percent subsidy on the price of nitrogen fertilizer. The policy experiments reported use 1994 prices because in 1996 the price of coffee was at an all-time high and not expected to remain there, and the rapid increase in real wages was judged unsustainable (owing its existence to the Brazilian *Plano Real*, the macroeconomic restructuring policy package, important components of which were abandoned in 1998). The use of 1996 prices for these experiments had similar effects to those seen when they were applied to the baseline. Diagrams depicting land use results for the experiments and reporting differences in other variables from those examined in detail in the baseline section are presented subsequently.

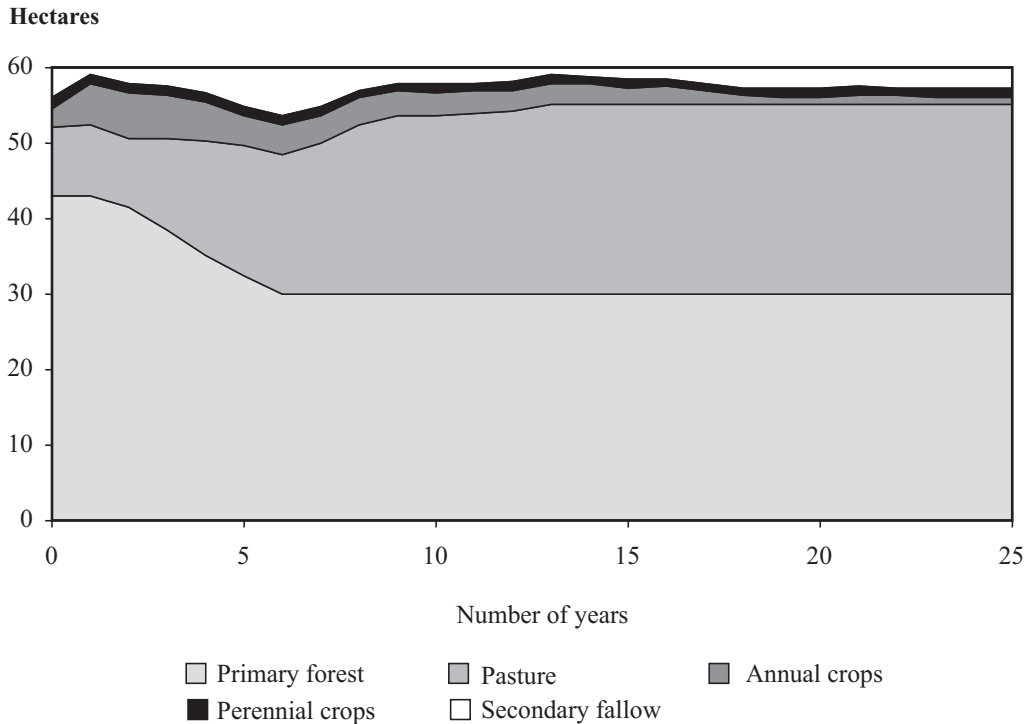
The 50 Percent Rule

In the baseline simulation, the federal law prohibiting deforestation beyond 50 percent of small farms is not enforced. Once this land use prohibition is introduced into the model (maintaining the prohibition on timber sales of any type), land use outcomes (depicted in Figure 4.15) vary greatly from

the less-constrained baseline. Once the 50 percent forest law is imposed, farmers maintain 50 percent of their land in forest, but they allocate virtually all remaining land to pasture and livestock production activities. Area dedicated to annual crop production decreases sharply once the 50 percent limit on cleared area is reached, while land in the perennial manioc stays roughly constant. Secondary fallow follows annual crop production up to about year 15, then expands slightly. When prohibited from deforesting more than 50 percent, the farmer is forced to choose between pasture and annuals (plus the fallow needed to support them), and finds pasture more attractive.

With these limits on deforestation, average annual profits fall to about R\$7,000 (a drop of about R\$2,000 per year, compared with the baseline). Labor hiring patterns change drastically; labor is hired for tree felling in May only up to year 9, after which hiring goes to zero, until small amounts of labor are hired for felling secondary fallow areas (again, in May) after about year 18. The household makes almost full use every month of the option of hiring out up to 15 person-days of labor. Perhaps most important, the composition of livestock activities changes markedly. While the size of the dairy herd remains roughly the same as that of the baseline, under the 50 percent rule scenario no beef cattle production activities are undertaken.

Figure 4.15 Land uses with the 50 percent rule strictly enforced



At the societal level, private financial losses to small-scale farmers caused by the strict enforcement of the 50 percent rule are at least partially counterbalanced by increases in carbon sequestered and biodiversity preserved. Using mean values for carbon measurements for particular land uses (Palm et al. 2000), the typical farm analyzed here, in shifting from an unconstrained forest use scenario to one which conserves 50 percent of private forests, would double carbon stocks from 4,120

tons of above-ground carbon under the baseline at the end of the 25-year period.⁷⁰ The total private *cost to the typical farmer* of this policy is estimated to be R\$6,475 = R\$50,635 (baseline scenario) minus R\$44,160 (50 percent rule enforced).

Subsidizing the Conservation of Forests on Small Farms

Once the issue of compensating farmers for income losses linked to regulatory policies (for example, the 50 percent rule) is up for

⁷⁰This is calculated as follows: (0 hectare x 206 tons/hectare for forest) + (50.6 hectares x 65 tons/hectare for pasture) + (3.7 hectares x 72 tons/hectare for annuals) + (1.1 hectare x 72 tons/hectare for manioc perennial) + (4.6 hectares x 84 tons/hectare for secondary forest fallow) = 4,021 tons for the baseline. Using the same method (and same order of land uses) but different areas coming out of the 50 percent rule simulation: (30 hectares x 206 tons/hectare) + (25.2 hectares x 65 tons/hectare) + (1.1 hectare x 72 tons/hectare) + (2.9 hectares x 84 tons/hectare) = 8,141 tons. The carbon savings implied by the 50 percent rule are thus 8,141 - 4,021 = 4,120 tons. Carbon amounts used here come from measurements taken in Acre, from ASB Brazil via Divonzil Gonçalves Cordeiro. (See Vosti, Witcover, and Carpentier 1998 for details.) Perennials with cycles longer than manioc (for example, coffee) had slightly higher per hectare carbon measurements (80 tons/hectare).

discussion, other compensation schemes that allow farmers to decide the optimal amount to be saved arise. For example, policymakers might pay farmers on a per hectare (or per ton of carbon) basis to retain forested areas. Alternative uses for forested land (and their expected returns) will determine the appropriate price for carbon in order to maintain a certain amount of forested land. In the baseline, the private value of the forest under current policy, price, and technology conditions is low (the net value of extractive activities per year is about R\$2.25 per hectare) and leads to complete deforestation in about 25 years. Deforestation and the use of cleared land would change as depicted in Figure 4.16 if farmers were offered R\$100 per hectare per year (or about R\$.70 per ton of carbon per year) for retaining forests. Deforestation is slowed significantly vis-à-vis the baseline; therefore, the stock of forest retained in year 25 is 15.6 hectares (versus zero for the baseline).

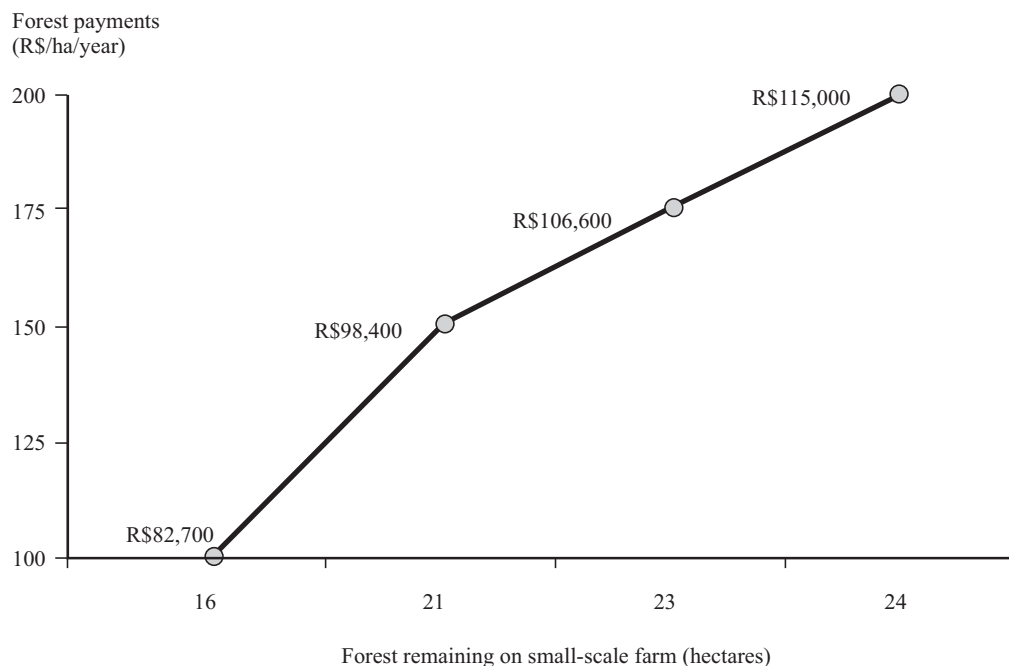
Several additional simulations are run to gauge smallholder response in terms of forest retained at higher prices per hectare (or per ton) (Figure 4.17). Doubling the price paid to farmers (to R\$200 per hectare per year) leads to about a 56 percent increase in forest retained in year 25—an own-price elasticity of 0.56. The per-hectare compensation leads to large increases in household income.

Small-Scale Managed Forests

Attempting to enforce the 50 percent rule is difficult and expensive in Brazil, particularly because, as the scenario above implies, farmers have strong financial incentives to behave differently. Increasing financial returns to forest activities could reduce the ability of regulations to slow or even halt deforestation (Browder, Matricardi, and Abdala 1996; Uhl et al. 1991), but only if returns are sufficient to alter land use patterns, given the demonstrated profitability of annual crop and livestock

Figure 4.16 Land uses with annual payments of R\$ 100 per hectare of forest



Figure 4.17 Trade-offs between forest payments and forest retained in year 25

Notes: “Forest payments” reflect scenarios in which different per hectare payments are made annually to farmers for each hectare of land retained in forest that year (for example, 150 represents a payment scheme of R\$150 per hectare of forest retained in each year, over 25 years; total real annual payments do vary for a given payment scheme, since farmers hold fewer hectares of forest as time goes on). “Forest remaining on small-scale farm” represents the stock of forest retained on farms at the end of each 25-year model scenario. Values are the net present value of the total farm income stream (inclusive of scenario-specific forest payments) over the 25-year scenario period.

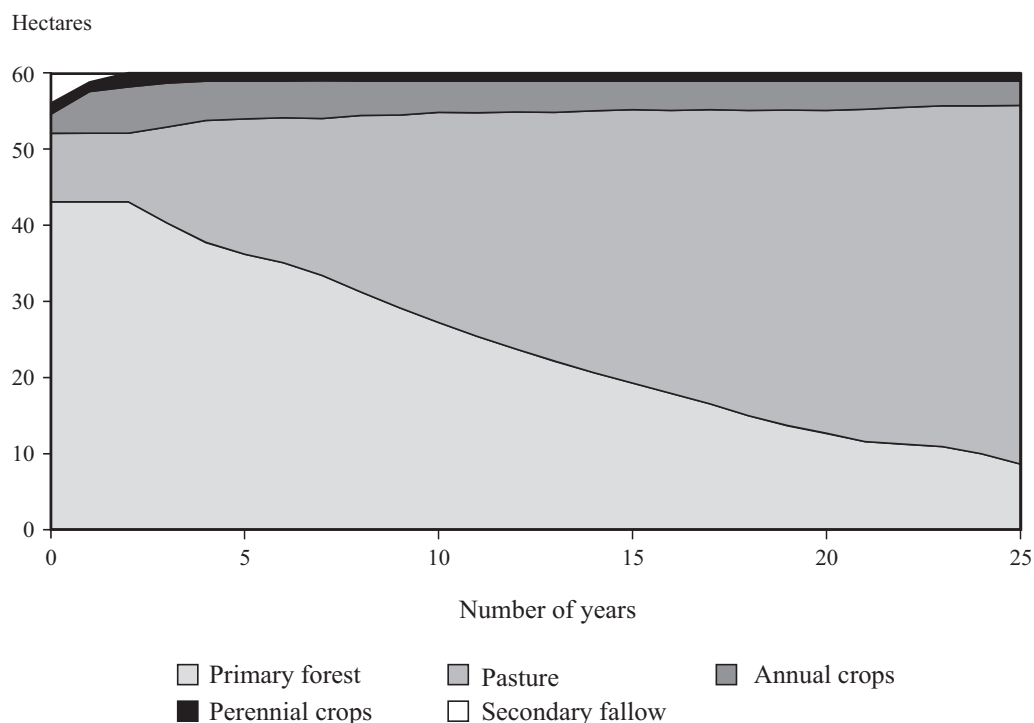
production systems. The model simulates the simultaneous removal of the 50 percent rule and the prohibition on the sustainable extraction of timber products from private forests.⁷¹ Land uses resulting from this simulation appear in Figure 4.18. Land held in forest in year 25 is approximately 10 hectares (versus the baseline of zero area in forest in year 25), land in annual and perennial (manioc) crop production resembles that in the baseline, but area in fallow goes to zero if sustainable timber extraction is al-

lowed. When sustainable timber extraction is possible, then more forest is retained, fallow is eliminated, and pastureland is slightly reduced.

The managed forest scenario generates differences in other parameters of interest vis-à-vis the baseline scenario. Both seasonal labor hiring patterns and the absolute numbers of person-days hired change. Much more labor is hired generally (still subject to the 15 person-day per month limit), and seasonal labor use patterns

⁷¹This simulation constrains the off-take of timber products to a predetermined rate judged by foresters to be sustainable over a 40-year wood production cycle (10 cubic meters of timber from selected trees per hectare, per year). No effort has been made here to assess the financial wisdom of adhering to these constraints, which indicates how difficult enforcement might be.

Figure 4.18 Land uses when sustainable managed forestry is allowed



reflect large increases in manpower dedicated to timber extraction activities during the May-September period (dry season), largely concentrated in July and August (due to fewer competing activities on farm). Engaging in small-scale managed forestry increases farm income, especially during years 5–9, prior to which substantial start-up costs reduce cash flow. The NPV of profit under this policy experiment is approximately R\$55,000; the baseline figure is R\$50,635, about 10 percent lower.

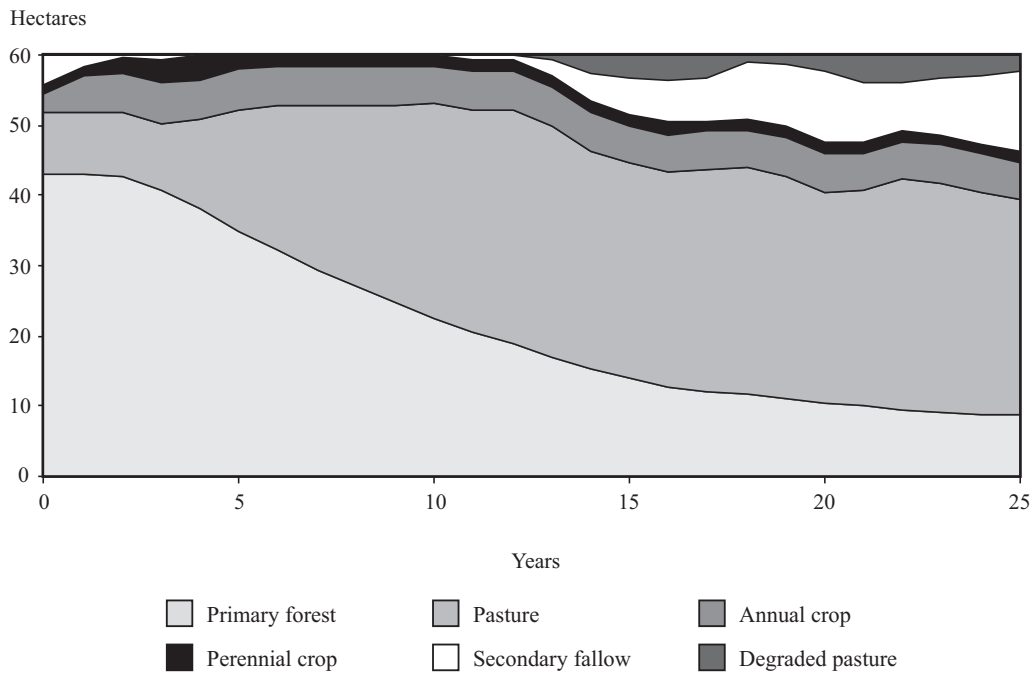
Technological Decay: A Default Scenario

The model can contribute to the debate about whether introduction of modern agricultural technologies takes pressure off forests or increases deforestation, and with what ramifications for farmer welfare. Figure 4.19 depicts land use and deforestation patterns that emerge by constraining the model to allow farmers to adopt *only* the

most basic (but still frequently observed) technologies for deforestation, ranching, extractive activities, and annual crop production (the V1 technologies are described earlier in this chapter and detailed in Appendix B). Area in pasture is considerably lower than under the baseline scenario, with roughly 10 hectares remaining in forest at year 25. Area dedicated to annual and perennial crops expands, with a large increase in secondary fallow land beginning in about year 13.

These changes in land uses bring dramatic changes in other key variables. Average (undiscounted) annual farm profits fall by approximately 80 percent (R\$1,381 versus R\$6,979). Income sources shift dramatically toward annual crops (which provide approximately 50 percent of the net present value of total output, compared with about 20 percent for the baseline). Beef cattle production begins in year 5 instead of year 9 in the baseline, though the proportion

Figure 4.19 Land uses with model constrained to low-level technologies



of beef cattle to milk cows remains similar to that of the baseline. The technologically constrained farm requires less labor than does the baseline farm, except during February, March, and April, when labor amounts roughly equal to those in the baseline are now allocated almost exclusively to annual crop production. Policy implications are clear: depriving small-scale agriculturalists of improved technologies and market access will slow deforestation over the short and medium terms, but this environmental gain carries with it large reductions in farmer income and welfare.

Subsidies for Chemical Fertilizers

If, as is sometimes alleged, small-scale farming operations at the margins of tropical moist forests are primarily nitrogen-harvesting processes by which farmers convert standing forest into soil nutrients for agricultural production, identifying alternative and cheaper sources of soil nutrients for

farmers could take pressure off standing forests. Scenarios that gradually reduce the price of chemical fertilizers from 50 percent of their 1994 market to 25 percent of that price, to making this input free to farmers are compared to baseline results (with fertilizer prices at about R\$1.20 per kilogram).

Figure 4.20 presents the results of a simulation involving a 50 percent reduction in fertilizer prices. Such a reduction slightly reduces deforestation rates, but the end effect on the stock of forest in year 25 is quite small (2.2 hectares versus zero for the baseline). The net present value of farm household profit increases to R\$55,248 (from R\$50,635 in the baseline).

More striking is the depiction of land use patterns under a scenario where fertilizer is provided free to farmers (Figure 4.21). Only about 7 hectares remain in forest in year 25, and other land use patterns remain about the same, but the net present value of profit rises to R\$77,115. The

Figure 4.20 Land uses with a 50 percent subsidy on fertilizer

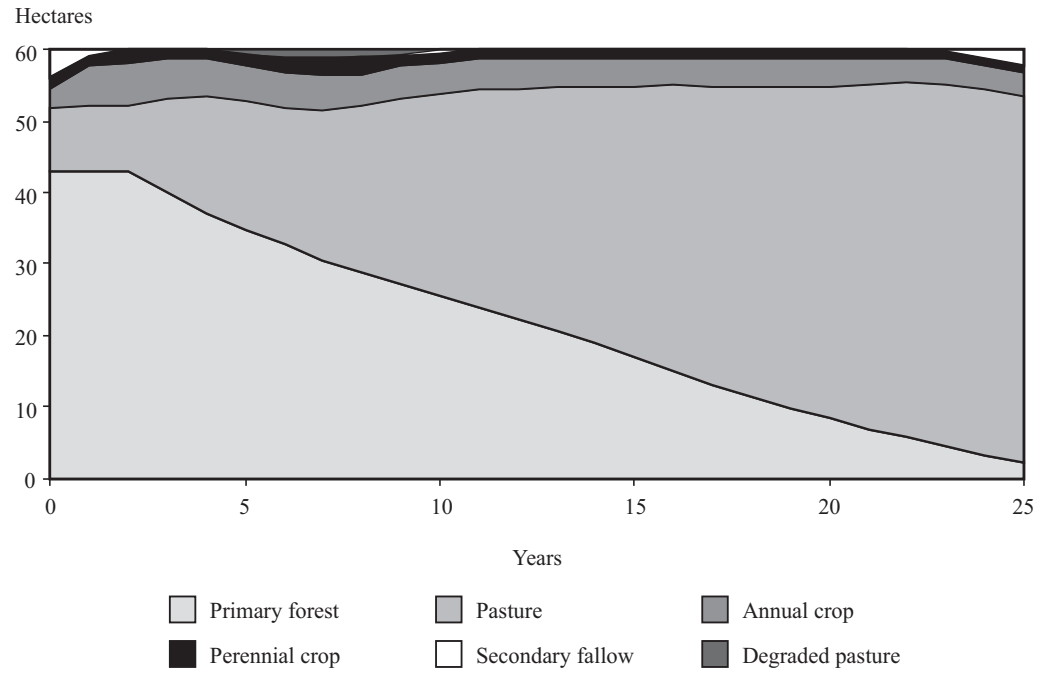
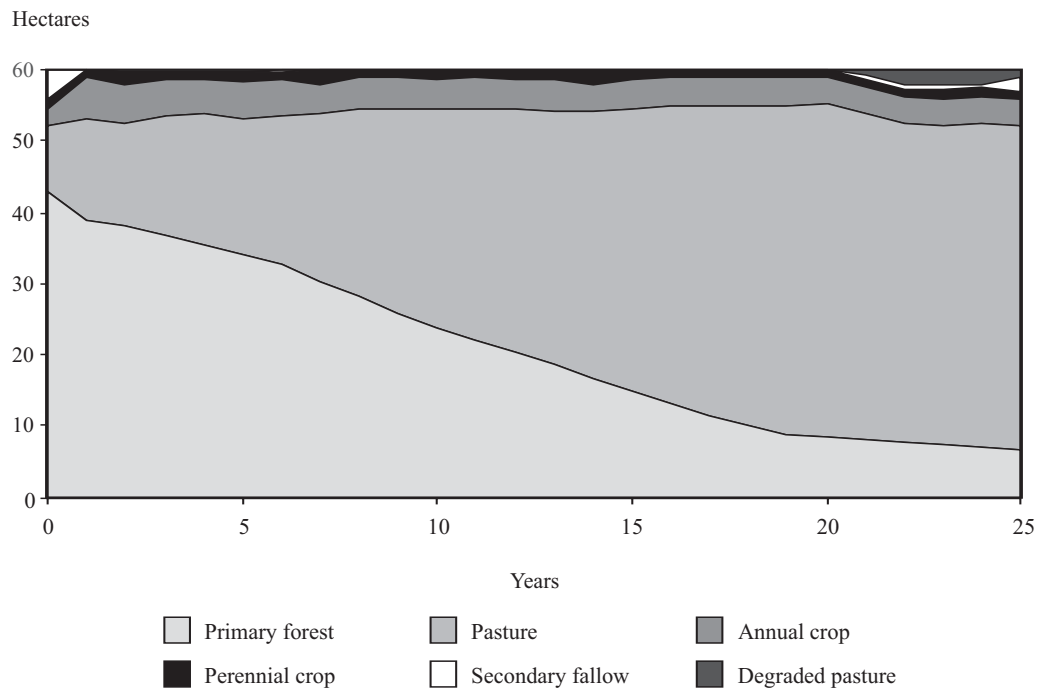


Figure 4.21 Land uses with a 100 percent subsidy on fertilizer



model does not support the scenario suggesting that nitrogen harvesting is the primary driving force behind smallholder deforestation patterns; it points to demand for cleared land rather than demand for nutrients to feed agriculture as driving deforestation for this group of landowners. Efforts to increase on-farm nitrogen availability via improved fallows or fertilizer subsidies are not likely to slow deforestation, although they may boost incomes.

A Multiple Policy Scenario- Managed Forestry and Fertilizer Subsidies

The final policy experiment combines two policy scenarios examined independently above, permitting small-scale managed forestry and instituting a 50 percent subsidy on chemical fertilizers. This policy combination adds value to the forest (the managed forestry element), while improving the incentives for land uses requiring more labor to establish and maintain than do cattle production systems. These uses might absorb manpower that would otherwise go either to deforestation or the establishment and maintenance of cattle production systems (or both).⁷² To illustrate the effect of such a policy combination under a range of relative prices, this section compares and discusses results under the two price scenarios—1994, with relative prices favoring pasture, and 1996, with striking shifts in prices to favor perennials. Under the latter price regime, this policy package can be thought of as truly “tree friendly,” improving incentives to manage and derive income from trees on both sides of the forest margin (promoting perennials in cleared area, and selective extraction within a still largely intact and regenerating forest). Results are

discussed in the context of expected longer-term trends for prices in the area, and possible responses to changed prices in the medium term.

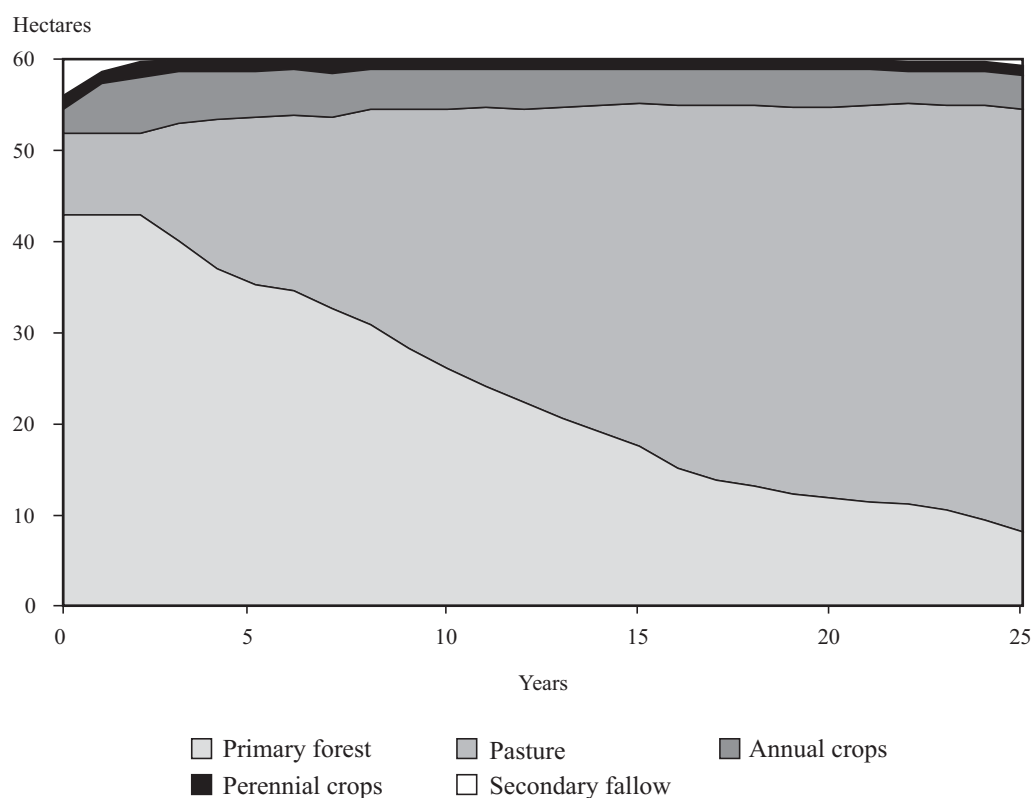
Figure 4.22 reports land uses for this multi-policy scenario with the 1994 price baseline as used in all previous policy experiments discussed here. Vis-à-vis the managed forest scenario alone (Figure 4.17), adding the fertilizer subsidy induces only small gains in forest retained in year 25 and the net present value of profit: forest retained increases by about 3 hectares (making the effect of these two scenarios in combination roughly additive with regards to their effect on the forest), and the net present value of profit increases from R\$55,000 to R\$58,783 (income gains being slightly less than additive). Given the weak land use effect of the fertilizer subsidy alone, it is not surprising that this policy combination does not yield tremendous gains in forest. The primary effect, again, seems to be a slight slowing of the deforestation rate and delay of the development of fallow to supply nutrients to annuals.

With fairly dramatic relative price changes (1996 versus 1994 prices, as outlined in Table 4.4), the archetypical farmer facing the multi-policy scenario can be expected to favor perennial tree crops even more than in the earlier case (recall the four-fold increase in coffee prices from 1994 to 1996). A separate simulation is run using 1996 prices, still permitting managed forestry (from 1994 to 1996 the price of timber transport fell 33 percent, creating an additional incentive for managed forestry) and still providing a 50 percent discount on fertilizers.

Figure 4.23 presents the land uses emerging from this 1996 simulation. Vis-à-

⁷²Perennial systems and annual/fallow rotations absorb considerably more labor than cattle production systems or sustainable timber management (the latter two being close in terms of labor requirements), and require more nutrients for production. The fertilizer subsidy in this scenario may encourage these systems apart from alleviating any incentive to deforest driven by a demand for nutrients (suggested by the prior experiment as not so important).

Figure 4.22 Land uses with managed forestry permitted and a 50 percent fertilizer subsidy, 1994 prices

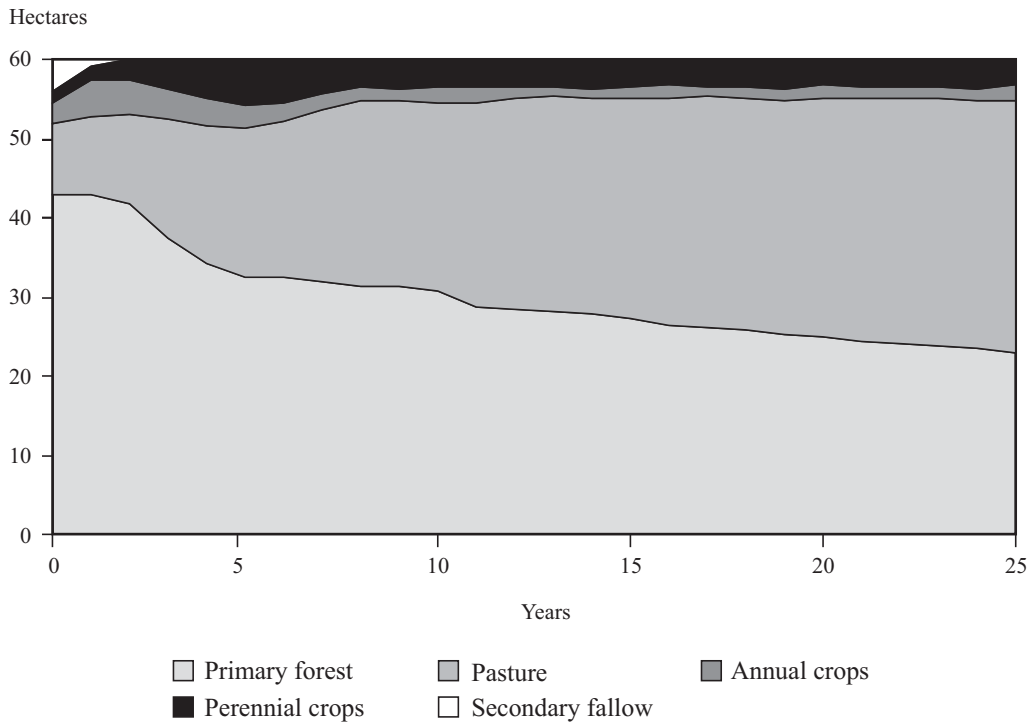


vis the same simulation using 1994 prices, forest savings are substantial (from 8 to about 22 hectares held in year 25), and the net present value of profits jumps to R\$108,305. Yearly deforestation has slowed considerably but still occurs throughout the 25 years, with pasture expanding as forest recedes. Perhaps more important, the composition of land in perennials has shifted, as coffee now occupies area that was dedicated to the staple manioc. As in the multi-policy scenario with 1994 prices, perennials expand into area previously in annual crops, but now the perennial area includes coffee. The combined area of annuals and perennials has not changed, but the additional area in perennials has absorbed family and hired labor that could have gone to deforestation or annual crop activities. There is still labor enough (and time) for the archetypical farmer to establish some additional pasture each year,

but the forest to pasture conversion process has slowed dramatically.

The “tree-friendly” package under a favorable price regime, then, appears to have considerable benefits for environmental sustainability in the form of forest conversion and for growth and poverty alleviation in the form of higher value of output. The scenario reveals the complex labor trade-off among land uses and its consequences for deforestation. Serious caveats, however, about the string of occurrences that need to be in line to achieve this result are in order. Recall that given the volatility of coffee prices (and the expected effect of price risk on adoption of perennials), and the fact that they were unusually high in the 1996 scenario, this price scenario represents an extreme peak, quite possibly an unsustainable one. Depending on relative prices, this policy combination could see results ranging from the forest savings and income

Figure 4.23 Land uses with managed forestry permitted and a 50 percent fertilizer subsidy, 1996 prices



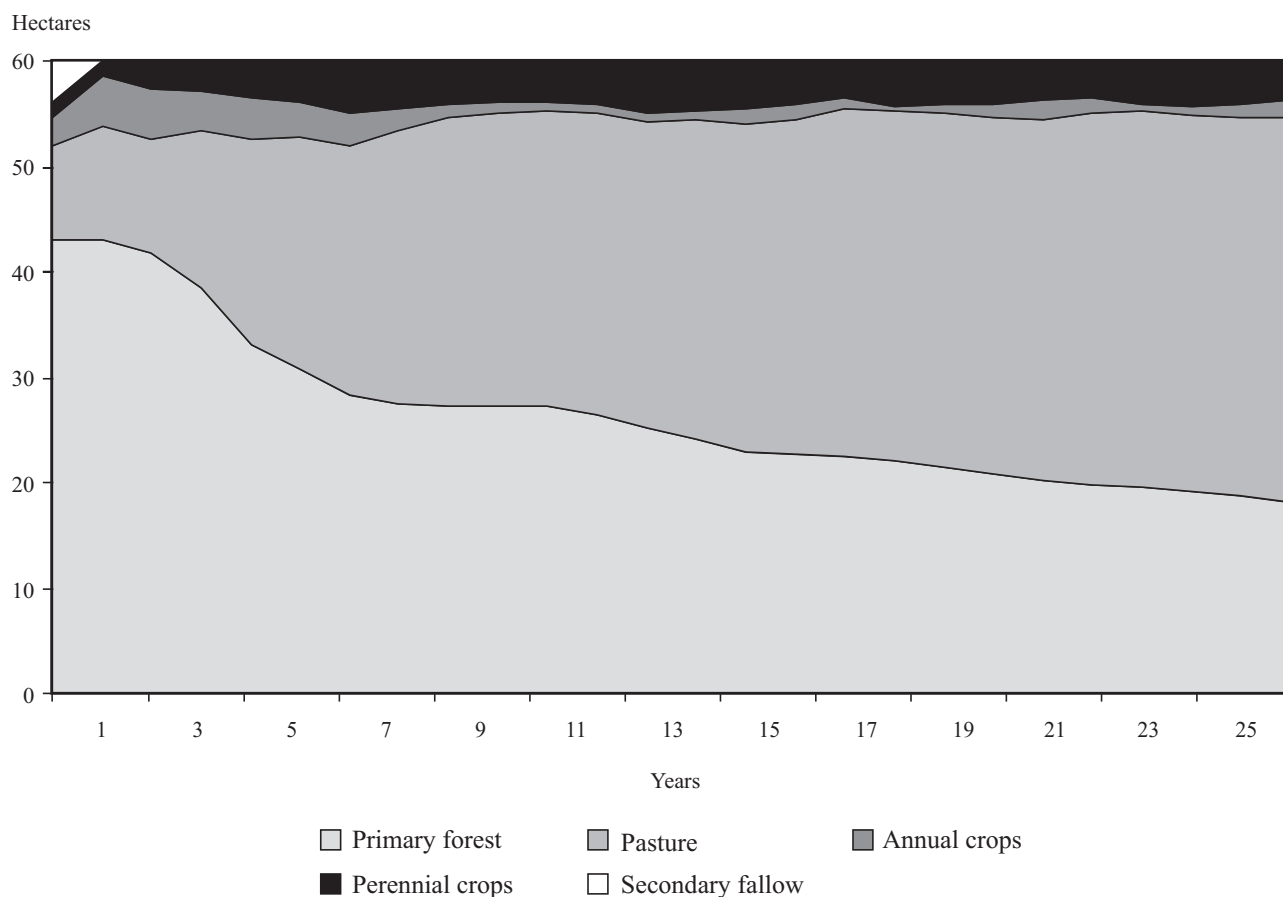
increases of the 1996 price scenario to those under the 1994 price scenario, where the same policy combination yields relatively small gains on both counts. Whether reality is more likely to fall toward one end of the spectrum or the other depends on one's expectations, not only regarding future prices (especially coffee prices) but also future improvements in labor market performance. If high coffee prices are unsustainable, and price risk further militates against adoption of perennial systems, scenarios closer to the 1994 price vector would have higher probabilities. If, on the other hand, the high cof-

fee prices do prove sustainable at least in the medium term, labor markets may respond in a way that reduces but may not erase the forest savings seen here.

Figure 4.24 presents the land use results for a final scenario: the multi-policy experiment with 1996 prices, this time allowing double the hired labor to flow onto farms—increasing the limit from 15 person-days to 30 person-days in any given month—but maintaining the limit of 15 person-days per month on household labor sales.⁷³ With twice the hired labor available—with other conditions as above: 1996 prices, managed

⁷³This is a substantial amount of extra labor—half a person-day per month per farm. But the nature of the labor requirement for this production system puts it within the range of reason for those months where labor demand is at its peak. Not just adult male but all types of labor can fill the requirement, and, while some skill is involved, it is not skill that requires intensive training. Indeed, near the Rondônia study site, seasonal coffee-harvesting work groups have begun to be trucked in from the cities (Samuel Oliveira, personal communication, 1997). For this scenario, the wage rate stays the same, reflecting some stickiness in the medium term. But even were it to rise a bit, the fact that the model farmer is not limited in hiring labor by amount of capital but by labor availability means that one would not expect the result to be substantially changed.

Figure 4.24 Land uses with managed forestry permitted and a 50 percent fertilizer subsidy, 1996 prices and relaxation of labor market constraints



forestry, and a 50 percent fertilizer subsidy—the farmer opts for converting more forest to pasture (forest in year 25 declines from 22 to about 18 hectares), while coffee continues to gain ground that annuals lose. Under altered labor use and cropping patterns, the net present value of profit shifts to R\$95,754.⁷⁴

This multiple policy experiment underlines not only the importance of relative prices to land use patterns but emphasizes

even more the key role labor availability plays in determining the extent to which the planting of labor-absorbing perennial tree crops diverts labor away from forest conversion and pasture expansion. The farmer finds it profitable to allocate some labor to the expansion of this labor-absorbing activity, but other labor is allocated to the expansion of labor-saving livestock. This is true even though the relative profitability of forest conversion is mitigated by the

⁷⁴The net present value of consumption is higher here than in the previous simulation because the situation is less constrained. The net present value of profits reported here is lower because it does not account for savings/investment beyond the model's final year, which means that end-year savings/investments are considerably higher under the previous scenario than under the current one.

availability of an activity that adds value to (and labor expended in) the forest. Once perennial tree crops (driven by relative prices) dominate the annual/perennial land and the labor needs of these systems are met, surplus labor flows to fell forest and establish pasture. An important policy implication of this result is that small-scale agriculturalists should not be expected to dedicate more than about 5 hectares to perennial tree crops without the unlikely scenario of relative prices even more in coffee's favor coupled with a massive change in labor availability.⁷⁵ Seasonal labor shortages constrain the amount of area that can go into these activities, and ability (sufficient labor) to manage cleared land in turn drives area deforested. When profitable, these activities in effect draw available labor to them and away from deforestation and pasture establishment (but not entirely); relaxing labor constraints will add more to pasture expansion than to the expansion of area to perennials.

Model Assumptions, Their Implications, and Future Research

Modeling resource allocation decisions and the economic and biophysical factors and processes that influence them requires simplifications regarding decisionmakers' objectives and knowledge base; the nature, generalizability, and stability of biophysical and socioeconomic processes and contexts in which decisions are taken; and a time-frame for resource allocation and consumption decisions. The bioeconomic model developed here is no exception. This section sets out the most important assumptions built into the model, addresses their possible implications for results, and suggests future research. Some assumptions relate to

how well the model captures current conditions on the ground; others relate to how those conditions are likely to evolve in the relevant time horizon. While not speaking to the latter, the model verification exercise described in the section on baseline results provides some basis for believing that the model structure captures essential elements of the land use process up through the time of the survey, despite the caveats and their implications discussed in the remainder of this section.

Stability of Farm Size and Ownership

The model is based on a 60-hectare farm, with no modifications to size of operational holding (renting in land, renting out land, land purchases, land sales, or land-sharing arrangements) allowed over the simulation period. Survey evidence points to a rise in the prevalence of land-sharing arrangements, especially for pastures. The timing for increasing pasture area and enlarging the size of the herd hinges on the annual agricultural cycle, herd demographics, and available resources. Being out of sync in terms of herd or pasture size has its costs: leaving pasture unused runs the risk of having it revert to forest fallow; overstocking pastures hastens their degradation. Land-sharing arrangements allow farmers to better manage this timing collectively, improving profit outcomes from those shown here.

Land purchases and sales were even more common in the study area historically than currently. Given that regression analysis (reported in Chapter 3) suggests that changes in farm size and ownership itself can influence patterns of deforestation and land use, this is a promising area for model modification, and one that would require detailed analysis of local land markets beforehand, preferably taking into account the

⁷⁵Note that the unlikely scenario making it profitable for land in perennials to expand considerably may create a different pressure on the forest.

maturing of the settlement projects themselves. Land markets could reflect values other than the relative profitability of alternative land uses as captured in the model—an option value for retaining forests or expected profits substantially different from those captured here, created by the dynamism of the developing frontier. This model does not speak to that possibility directly, but it illustrates that observed land use patterns can be substantially explained by assuming that land values reflect expected profits as captured in the model. The model incorporates, moreover, what the regression indicates as the more important effects of land status upon arrival and recent land use. It also illuminates behavior under land constraints that might be considered a shorter-term reality for most farmers, and it points to a potential for land expansion or transfer as forests on currently owned land are exhausted.

To the extent that land markets do reflect the model's rendering of relative profitability of alternative land uses, allowing land transfers would likely affect the locale and timing of deforestation more than the essential forest-to-pasture conversion finding. In addition, to the extent that land markets in the area are developing, and the assumption of no economies of scale is and remains accurate (more on this assumption below), the importance to land use of changes in farm size and ownership should recede over time, approximating the situation in the model.

If the assumption of constant household size and demographic characteristics were relaxed, on the other hand, it could have important land use ramifications. A simple model of aging, with household members constrained to stay on the farm, would introduce interesting life-cycle issues. A more realistic (and considerably more complicated) approach, however, would be to endogenize household size over the time horizon, with effects on household income and deforestation hinging on relevant assumptions about (1) off-farm investment and em-

ployment opportunities, (2) household risk considerations, and (3) internal household decisionmaking.

Household Objective of Maximizing the Net Present Value of Consumption

Farm households are assumed to maximize the net present value of consumption over the specified time horizon. As suggested in the discussion of land markets, maximizing asset value instead would result in similar deforestation and land use patterns, as long as the streams of financial benefits generated by land uses determine asset values (of farmland, forest land, and livestock herds, for example). Deforestation and land use patterns would be different if an asset-based optimization procedure was adopted and something *other than* financial flows determined asset values. In the absence of major changes in international policy and local compensation mechanisms that could affect asset values (especially for forests) in this way, there is no reason to believe that changing the arguments in the objective function in this manner would greatly alter model results.

That the objective function does not involve maximizing household preferences has perhaps more far-reaching implications. Although households must consume the minimum required for a comfortable life, they can also use their generated profit streams to purchase consumer durables (such as sewing machines, bicycles, parabolic antennas, or television sets), which survey data suggest are increasingly common. The timeframe for availability of cash for purchase, but not timing of particular types of purchases, is determined by the overall decisions taken to maximize the net present value of consumption over the whole period. Given limited credit markets and other market imperfections in the model, this characterization of consumption could have several important implications for production and land use. If preferences on timing of consumption of particular

types of goods (apart from risk, which is discussed separately below) were included, this could affect how the household decides to allocate money stocks on hand to current consumption versus investment for future production in any period. As in other consumption baskets, the relative importance of particular products would be expected to change with shifts in income (relevant for the dynamic aspect of all simulations of this model) or relative prices (relevant for some simulations of this model). In addition, because the model's list of production investments is limited to items directly related to particular production activities, it overlooks the production benefits from some of the consumer durables listed (for example, a car could improve transport to market and a television set could provide market or technology information). The timing of such purchases could be significant to land use outcomes but is not captured by the model. To the extent that including these consumption aspects diverts resources from (or provides additional resources for) production activities, the result could be slower (or faster) deforestation from what is seen in the model.

Perhaps the most important gap created by the exclusion of preferences from the objective function given the sensitivity of model results to labor is the absence of explicit household utility for leisure time. Because of imperfect input markets, decisions about allocation of time to labor or leisure, based on household preferences, would affect production activities even in a one-period model. In the dynamic setting of this baseline model and its simulations, this effect is compounded by the fact that leisure consumption is expected to rise as income rises. Including a preference for leisure as a normal good would decrease labor available to the household as income rises, slowing the deforestation process, and perhaps affecting the attractiveness of labor-intensive activities such as perennial tree crops in simulations that currently favor their adoption (albeit limited in scale).

Finally, the objective function itself is defined at the level of the household, implying that households behave so as to maximize their collective benefit. The more specific assumption of a single decision-maker or consensus decision regarding production activities is formulated from evidence on decisionmaking garnered in the survey. While models of household behavior exist in which bargaining and individual control over assets play a central role, this level of detail does not seem warranted to capture essentials of land use processes at this study site.

Limitations on Household Investment and Production Technologies

One could also argue that the range of investment opportunities available to the archetypical household is too narrow. As currently specified, farmers can only invest on their farms and only via specified land use technology options. The effects on deforestation and land use of expanding the set of possible on-farm and especially off-farm investments cannot be determined a priori. Off-farm investments such as schooling of children or investments in commerce have ambiguous effects on deforestation: they may deplete cash and labor resources and reduce deforestation over some period of time, but eventually they either provide additional cash to hire labor for forest felling or draw resources away from agriculture.

Perhaps more important to this characterization of agricultural production activities is the fact that household on-farm investment and production behavior more generally is limited to choices among fixed-input (Leontief) technologies with exactly prescribed management practices, a by-product of the model's linear construction. The implications of including additional types of production investments are discussed in the subsection on the objective function. Rigidities of behavior and input use within types of production activities imposed by the model structure may, however,

also have important implications for model results. The implications may become more important as simulation conditions depart from those observed for the baseline. Mitigating the effect of these rigidities is the ability of farmers to choose the amount of land to allocate to a given production technology (and to devote more than one parcel within the lot to production of the same output under different levels of technologies). This in effect creates formulas by which farmers can substitute inputs in production. The archetypical farmer in the baseline finds this situation profitable, as evidenced by the coexistence of V1 and V2 technologies on farms for several production activities described in the section on baseline results.

These formulas, however, are themselves rigid, and do not reflect the capacity of farmers under real conditions to juggle resource allocations in response to changed factor and output prices, including freely choosing the time path of resource degradation, with profit motives in mind. Even small divergences from the patterns shown here could accumulate over the time horizon of the model.

Since labor has a high shadow price and can be easily reallocated across activities and over time at the margin, the capacity to substitute land or capital for labor (or reallocate labor and leisure, as discussed above) could change income or land use results in any given time period. That said, fungibility of labor across activities and over time is limited, however, by who on farms can physically perform important tasks (such as deforestation) and when these tasks can usefully be performed.

Similarly, levels of overgrazing—the degree to which farmers can choose to mine the pasture resource—are constrained in the model within the technology choices. Given the importance of pasture and herd growth to the model, truly endogenously determined levels of overgrazing might have different results but would likely affect the timing of deforestation more than

the basic pattern. Likewise, the sustainable timber extraction simulation imposes techniques laid out by researchers, but even if restrictions on output flow and the amount of “collateral damage” allowed remained, methods (resource allocations) used by farmers to achieve those ends would likely be different from the experimental technology.

A second by-product of the model’s linear construction is an assumption of constant returns to scale. This adequately represents some agricultural activities in the region, especially within the area ranges observed in the field, but it may not reflect the realities of cattle production, particularly where more advanced methods of herd and pasture management are employed. Jones et al. (1995), for example, found evidence of increasing returns to ranching in Ouro Preto do Oeste, Rondônia, as did Mattos and Uhl (1994) and Arima and Uhl (1997) for specialized ranching operations (rearing and fattening) in the eastern Brazilian Amazon. That said, such specialized activities have yet to appear in this study area, and when the choice of technologies in the model included the most sophisticated pasture/management technologies available, according to local agricultural researchers, it was never chosen by the archetypical farmer in any of the simulations presented here. Still, it could be relevant for scenarios involving relatively long time horizons, with changing factor endowments (see the subsection on this below), where the likelihood grows smaller that the set of technologies presented here is comprehensive. If incorporated into the model, scale economies in pasture would add to factors that favor pasture creation (the speed of which is constrained by other elements in the model, notably labor for clearing). Nevertheless, introducing nonlinear relationships among key inputs in important production activities would be a useful extension of this and other bioeconomic models (see, for example, Barbier 2000).

Risk

Farm households face no risk in the model.⁷⁶ This is a clear deviation from reality; agriculture is risky business everywhere on earth. This area's risks include those associated not only with production (climate, pests, diseases, and runaway fires) and price but with uncertainties regarding marketing chains, health, employment, and policy (Nepstad et al. 1999; Vosti and Witcover 1996b). A model could incorporate risky outcomes through exogenous shocks to which farmers must respond *ex post*, or could take a more sophisticated *ex ante* approach in which farmers' expectations and attitudes toward risk would be modeled. The absence of insurance markets to cover risk favors livestock production systems, as can be seen in the widespread use in the survey of livestock as a mechanism for holding assets that can be liquidated in times of need. Cattle production systems themselves can, however, be subject to risk—recall the recent problem with widespread death of the pasture *brizantão* (more on this in the subsection on longer time horizons). Different types of risk, however, can have additional effects on household production decisions.

Accounting for yield or price volatility would not be likely to close the substantial gap in expected profitability between forest and pasture activities. These types of risk would probably skew activity choice toward livestock production systems because of characteristics that make cattle the asset-holding mechanism of choice, including (at least historically) lower price volatility and more predictable production patterns in this area of the Amazon (Faminow et al. 1999). The speed of deforestation would depend on whether favorable or unfavorable realities played out. Introducing weather-in-

duced and other production shocks, perhaps via links with the Decision Support System for Agrotechnology Transfer (DSSAT) crop growth model would be a useful extension of the model (IBSNAT 1994).

Risk of injury (especially during forest felling) and illness (primarily malaria) is great, especially during the initial phases of colonization (de Bartolomé and Vosti 1995). Losses of labor and cash associated with malaria alone can be large enough to reduce deforestation rates and undermine efforts to intensify agricultural activities; in the extreme, these losses can cause abandonment of farms. Employment risk can affect farmers' expectations of availability of off-farm labor and thus allocation of labor on-farm. Incorporating these sorts of risks into the bioeconomic model would yield important insights into resource use decisions, and especially into poverty-environment links. Finally, risk associated with an uncertain policy environment could cause farmers to shy away from production activities requiring greater up-front investment (such as perennial tree crops).

Farmer Omniscience about Economic and Environmental Processes

The archetypical farmer is assumed to have complete and accurate knowledge regarding economic factors (such as input and output prices), biophysical processes (such as soil nutrient losses associated with annual crop production), and technologies that affect resource allocation decisions over the entire time horizon in question. The constant relative price assumption is a simplification that illuminates the role of prices in the deforestation process more clearly. Additional model simulations could incorporate different models of price expectations

⁷⁶The notable exception is the case of edible bean production: yield parameters were adjusted downward to incorporate routine crop losses associated with mold and mildew.

from the one-year lagged model presented here, including projections of long-term price series based on, for instance, futures prices instead of constant prices. Model testing suggests, though, that deforestation rates are responsive only to major changes in the value of forests or forest products vis-à-vis agricultural products, which seem unlikely in the immediate future, since they would require major and yet unknown international policy actions.

The assumption that farmers have access to the best available knowledge about relative prices fits with the situation modeled here, where settlement areas are relatively mature, farmers have access to radios and other forms of communication, and are visited by product buyers. Complete information about technology and how production is affected by particular on-farm biophysical conditions, however, may be less widespread, even among well-situated farmers, given the inability of extension agents to cover the broad areas in the projects and disseminate materials to cover the heterogeneity in soil conditions. Many of the details associated with the inability of Amazonian soils to support long-term cropping are unknown even to the scientific community. Still, knowledge of general patterns of yield declines, especially for annual crop production systems, is common in the region, with the possible exception of recent migrants moving to newly settled areas. Indeed, the fact that these are no longer newly settled areas means farmers' knowledge about likely agronomic responses to somewhat familiar technologies is likely to be fairly accurate.

Local Market Conditions

It is also assumed that farmer activities will not affect local or regional markets, thereby prompting changes in relative prices for inputs or outputs relevant to farmers. The model's primary purpose, however, is to illuminate implications of current behavior patterns, more than to make realistic predictions of the future. That said, for many in-

puts and products, the assumption of little regional market effect is defensible. The western Brazilian Amazon is becoming much more integrated into national and regional markets, so producers and consumers face prices determined at those broader market levels. Where smallholders contribute significantly to the supply of products, with markets that are not well integrated into the national economy, the aggregate effects of farmers similar to the archetypical one here could shift local equilibrium conditions. Demand and supply for agroforestry products and nontimber forest products are more locally determined; for these products, large increases in supply will surely drive down prices. Incorporating price responsiveness into the model might alter farm-level decisions regarding these products, but again, doing so would likely worsen their expected profitability and fuel rather than brake deforestation. Regional market determination may also characterize milk and livestock markets, however, but in this case the supply response is occasioned by growing regional demand. To the extent that growth rates in regional supply and demand match, the overall effect on price of farmers' collective actions will be mitigated. The effects of these broader changes on labor market restrictions and milk quotas are more problematic for the model in its current form, and fall under the rubric of model simulations without these restrictions.

Longer Time Horizons

The 25-year horizon was chosen to capture relevant policy responses in the simulations selected. Extending this horizon another 20 years shows that, after forest is exhausted under the baseline scenario, farm profits eventually fall and fallow rotations become more prominent on the landscape. These results should be interpreted with caution, however, in light of the fact that the model's shortcomings, highlighted in this section, are more likely to cause model results to diverge from likely realities as the model's

time horizon is extended further into the future.

For that reason, for models on such a time scale, the absence of endogenous shifts in household behavior (such as innovation of new technologies) or the policy environment in response to changed conditions makes results problematic. Behavioral shift parameters that dictate changes in household responses to economic and biophysical factors could be the result of changes in on-farm circumstances (such as changes in the demographic composition of farm families over time or biophysical conditions) or from changes in perceived incentives even in the face of constant prices (for example, farmers may behave differently once they approach or have exceeded the established legal limit for deforestation and consequently risk fines). Other types of mid-scenario shifts might be the result of endogenous policy changes, such as new forestry laws brought about by greater-than-expected deforestation rates, or agricultural research prompted by agronomic

difficulties. The recent difficulty with death of the most prevalent pasture *brizantão* is a case in point. Pasture varieties tend to have their own life cycle in a particular ecosystem, with pests' ability to adapt accumulating over time and accelerating where poor pasture management lowers resistance. The model does not account for the farmer's response to this situation: he may reformulate the pasture by burning to control pests or abandon pastures because it is cheaper to clear new forest area—moves that have caused severe economic losses in some cases (J. Valentim, 2000, personal communication). This particular scenario could usefully and relatively easily be incorporated into the model. More broadly, integrating these sorts of mid-scenario corrections into farmer behavior and policy context would alter results regarding deforestation, use of cleared land, and income, but modeling these endogenous changes lies well beyond the scope of this farm-level research.

CHAPTER 5

Conclusions

Roughly 7,600 square kilometers of tropical rainforest in Brazil were cut down and burned between 1995 and 1997. These forests were of commercial value, and the land they stood on is of agricultural value to both the small-scale farmers who use cleared area to meet livelihood security needs and the regional economy that benefits from increased aggregate production for consumption and trade. But, these forests also provide important services of global benefit, most notably the sequestering of carbon and other greenhouse gasses and their contribution to biodiversity. Society also places noneconomic values on forests. Between the private and global social benefits fall the local benefits provided to individuals and communities living near forests: clear air, hydrological services, and parklands among them. Private and social values of forests are likely to be at odds until mechanisms exist to make social values a part of private decisionmaking. In the absence of such mechanisms, the trade-offs among environmental sustainability, growth, and poverty alleviation associated with different uses of the forest need to be better understood by those who would try to balance the needs of forest inhabitants, local communities, and the broader global community.

Small-scale farmers (the focus of this report) have been responsible for much of the most recent wave of forest clearing—a process difficult to halt by legal prohibitions alone given the strength of current private incentives to clear land. Several key questions emerge: (1) How much do small-scale farmers and the agricultural sector benefit from deforestation, and what are the effects on the environment? (2) Once forest is cleared, are the uses undertaken sustainable? That is, do they continue to bring in profits? If not, can agriculture or forest-related activities (where some forest remains on farm) be intensified to make the land more profitable? (3) What policies in lieu of or in addition to outright prohibitions might be effective in slowing deforestation by smallholders and making subsequent land uses more sustainable, without sacrificing income?

The report is based on a common theoretical framework of household-level behavior (including land use decisions) under circumstances constrained by the extent to which they rely on their own resources or have access to others off farm. While relying on representative field data, the report makes use of several analytical tools. Descriptive analysis sets the stage, providing background on policy context, market and marketing structure, local community factors, farm-level biophysical characteristics, and household-specific endowments of land, labor, knowledge base, financial resources, and access to markets or other local trading opportunities. This information is critical for establishing farm, farm household, and biophysical characteristics that influence land use patterns, and for assessing the extent to which existing land use patterns affect development objectives. The descriptive analysis also brings sample descriptive statistics to bear on the question of local land use in a framework that touches on

the key aspects of the theoretical model (dynamic aspects, biophysical processes, household endowments, and local institutional contexts, including sources of uncertainty and attitudes toward risk that affect profit expectations). The framework evaluates smallholder adoption of prevalent and experimental technologies defining land use systems.⁷⁷ Its preliminary findings set the tone for much of what follows, using more sophisticated analytical tools. Such analyses of land use systems provide longer-term views of the impact of production systems (comprising different sets of production activities) on sustainability, growth, and poverty alleviation.

Regression analysis exploits sample heterogeneity in these factors to isolate those most important for determining observed land uses, given common national and regional price signals and policies. It provides empirical assessments of the effects of, for example, land tenure and local organizations on deforestation and patterns of use of cleared land. It also sheds light on the extent to which land trading and farmer transience affect land use patterns. This tool cannot isolate, however, farm-specific responses over time to relative prices, different policy contexts, or their own shifting resource constraints, particularly wealth. A farm-level bioeconomic model picks up where the regression analysis leaves off, focusing in on precisely these dynamic elements of farmer responsiveness, incorporating biophysical processes already known to affect land use in an explicit way. It complements the regression analysis, since it can test for the effects of particular factors—such as institutional contexts—on land use decisions. Unlike the regressions, however, it cannot provide evidence that these factors make a difference for land use in real-life situations, with all of their uncertainty, risk,

and complexity. As constructed, the bioeconomic model cannot pinpoint forces driving land transfer or farmer transience in the region. Using results from descriptive and regression analyses, however, the bioeconomic model highlights how on-farm competition across land uses for specific scarce resources affects deforestation, land use, and income outcomes. To isolate the dynamic elements, the bioeconomic model abstracts away from farmer heterogeneity to define the characteristics of a representative farmer, including the quality of the farmer's land. The off-farm market and institutional context is also set for this representative farmer, including relative prices and the available technologies. The choices made for the representative farmer are grounded in the descriptive analysis of the sample to arrive at a baseline scenario of deforestation/land use and income based on current conditions. The range of sample realities and other policy contexts provide the basis for simulations, the results of which are compared against the baseline.

Results are relevant for small-scale farming in the context of the western Brazilian Amazon and in other areas with similar relative factor endowments—particularly labor scarcity and land abundance amid imperfect credit markets—and the general economic context of expanding but as yet incomplete links between farmers and regional markets, and regional and broader markets. At the time of this report, markets were growing and vibrant; effects would be different in a broad economic downturn, but that scenario lies outside the range of conditions that can be confidently speculated on here. The research methods developed and deployed in this report are relevant for even a broader set of cases where the issues of poverty, environment, and growth are simultaneously addressed.

⁷⁷This framework has been extended elsewhere to encompass impacts on carbon sequestration (Carpentier et al. 2000) and biodiversity.

A combination of analytical tools such as those deployed in this study—targeted toward describing the problem, assessing how heterogeneous factors within the sample affect the problem, and explicitly considering the forward- and backward-looking dynamic elements of the problem—may be needed in order to reach conclusions that lead to comprehensive and credible policy advice.

General Conclusions

Deforestation and land use decisions by small-scale farmers at the margins of the western Brazilian Amazon are driven primarily by the relative profitability of alternative cropping, livestock, and extractive activities and labor scarcity, which currently combine to favor livestock production systems at the expense of other activities, thus promoting the steady conversion of forest to pasture. Seasonal swings in rainfall, and consequently in labor requirements of different production activities, condition both profitability and labor scarcity; some potentially profitable alternatives are not adopted as the result of labor shortages during the initial stage of property development or key points in production or maintenance cycles.

When they grow more profitable, labor-absorbing activities become more attractive to farmers and have a braking effect on deforestation, but the overall pattern of forest conversion with pasture expansion over the longer term persists. Conditions favoring current labor-using technologies and land uses are, moreover, unlikely to persist, and if they did, would spark general equilibrium responses that would point to, again, more deforestation. More forest currently stands than would be the case if labor was not so scarce: labor availability is not only limited during the two-month period when it is feasible to fell trees, but throughout the year. Labor scarcity also puts limits on how much land can be managed once it is cleared, and lack of management has a

cost—the regrowth of forest and the need to clear again (but the land benefits from the nutrients recouped).

Clearing forest for agriculture has largely meant less poverty in deforested areas: forest “assets” have been converted to physical assets, both on and off farm. Not all farmers have succeeded in bettering their lots, however: some are still struggling to capitalize, and others may have already abandoned agriculture, although there were no signs of severe malnutrition in the projects.

Policy changes could induce small-scale farmers to modify their deforestation and land use patterns, but new policy instruments are needed to make sure this would also improve incomes. Regulating deforestation has so far largely failed because forest clearing is profitable for farmers, and making sure that smallholders follow the rules is costly. Improving enforcement without changing incentives would also be costly, and unless care is taken, those changes could leave farmers worse off. Indeed, the still-substantial group of worse-off farmers in the sample tended to deforest less. There is some evidence that seasonal isolation, in particular, shifts farmers toward planting more subsistence annual crops in order to preserve their livelihood security. Price and technology policies can change the pace of deforestation and alter patterns of use of cleared land, but under reasonable and foreseeable scenarios, forests will continue to fall and the bulk of cleared land will be dedicated to pasture. Best-case scenarios indicate that perennial crops are profitable in the long run and will significantly reduce the pace of clearing, however. Emerging markets for carbon may offer a new weapon for slowing deforestation, but policy action is needed to address issues of implementation, including transaction costs, in the context of small-scale agriculture.

Finally, the institutional and especially the commercial contexts in which deforestation and land use decisions are being

made are changing rapidly. The private sector, virtually absent during the early stages of colonization in these areas, has matured and expanded substantially, providing new income-generating opportunities, but these opportunities focus almost exclusively on products produced at some cost to forested land. Public sector activities have declined markedly, creating some key gaps in service provision, which are being filled by local organizations, NGOs, and sometimes the private sector. These social networks play an important role for land use patterns, either by lowering the costs to farmers of trading in formal marketplaces or by providing information on trading opportunities that relax on-farm resource constraints.

Smallholder Land Use Patterns: Current Patterns, Key Determinants, and Future Scenarios

- *Trajectory of small-scale agriculture.* Deforestation will persist under current economic, biophysical, and policy conditions because the returns per labor unit to agricultural activities are greater than those generated by forest extractive activities. So, while small-scale farming systems can generate sufficient income to sustain farm households of fixed size and demographic composition and contribute to regional growth, they will not retain natural forest over the 25-year time horizon of the model. While the ability of farming systems to support additional population pressure has not been tested directly, regression analysis provides indirect evidence that farms with greater household labor endowments or smaller forest stocks moved into more intensive land uses.
- *On-farm determinants of deforestation.* Once smallholders are established on their farms, the harvesting of nutrients from the forest (via slash-and-burn agriculture) is *not* the primary motivation at farm level for clearing forests. Rather, it is the demand for cleared land for agriculture that drives deforestation. Therefore, efforts to slow deforestation by identifying alternative and cheaper sources of nutrients (especially nitrogen) will probably not succeed. Other land quality characteristics relevant for agriculture—waterlogging, slope, and rockiness—may have more of an effect on deforestation but that impact is not via overall suitability of land for agriculture, but via their influence on specific land uses with specific technologies with specific factor intensities. Demand for cleared land, moreover, is critically shaped by household endowments of labor and cash, and by the household's access to input and output markets. These conditions affect specific land use choice and consequently deforestation and household income.
- *Stability of land use patterns.* Overall land use patterns of smallholders are not particularly sensitive to changes in relative prices or technological advances that do not affect labor requirements. That is to say, small changes in the financial incentives to farmers to modify product mix or deforestation rates will not generate large changes in either. This is true at the level of the operational holding for several reasons: (1) extensive livestock production systems continue to be most attractive to smallholders because they are flexible and require less labor, although they do not always offer the highest returns to land or labor; (2) seasonal labor bottlenecks preclude the broad expansion of labor-intensive production systems, such as agroforestry systems, which are precisely the types of systems needed to brake deforestation; (3) market and other risks are high for many of the products of agroforestry systems; and

(4) switching from pasture to most other land uses can be agronomically and otherwise complicated and hence costly and slow. This financially and agronomically induced stability of current land use patterns will challenge policymakers, who will have to increase the amounts by which, and the time frame during which, they modify farm-gate incentives, if large and sustained farmer responses are to be expected. That said, regression analysis identifies factors that already make a difference in proportions of particular land uses, pointing to policy levers that need to be targeted or considered in making any such changes. It also suggests that urban links are drawing resources out of agriculture and taking pressure off forests, although these effects have only been observed in the short term: long-term results hinge on the relative profitability of accessible opportunities within the different sectors.

- ***Environmental costs of small-scale agriculture.*** The large losses of forest at the farm level imply losses in carbon emissions and biodiversity, but soil degradation following deforestation also has consequences for farmers. Assessments of environmental costs must take into account all land uses (not just deforestation) and the trajectory of these land uses (not just a snapshot at one point in time). For example, small-scale farming can replenish some above- and below-ground carbon stocks, and a *trajectory* that includes regrowth of secondary forest between cycles of use has a different carbon profile than one that involves permanent conversion to pasture. Similarly, cleared land can be managed in ways that retain more above-ground (and perhaps below-ground) biodiversity, and policy can influence some management strategies. At a spatially more aggregate level, the way that groups of small farmers man-

age their land may make a great deal of difference in how the abutting forest ecosystem is affected. But few policy instruments exist today for fine-tuning land use by smallholders to address such local cross- or off-farm effects.

- ***Private benefits versus environmental costs.*** Because agriculture on cleared land is profitable, persuading farmers to deforest less will not be easy, or, in the aggregate, cheap. Still, based on some figures currently in use for the worth of carbon alone, the social gains from saving forest outweigh private profitability forgone by not deforesting, but no mechanism for realizing transfers exists. However, the volume of savings to society is large enough to suggest that investments in establishing such mechanisms could be worthwhile. If credible and sustainable mechanisms for compensating farmers for forest (or carbon) retained can be developed, smallholders will respond.
- ***Growth from small-scale agriculture: To intensify or not?*** Farmers will deforest at a slower rate if they are using traditional technologies rather than modern ones, which raise agricultural productivity. Eventually, however, these farmers will probably take down roughly the same amount of forest, and their incomes, the values of their farms, and their contribution to GDP will be substantially lower. In short, technological stagnation will slow deforestation, but it will also slow poverty reduction and regional growth. To increase incomes and preserve forest, technology and policy packages need to improve profitability on already cleared area without raising farmers' incentives to clear more land. Investments in technologies that explicitly target recuperation of cleared areas for intensive use and supplemental measures that make it

more costly for the farmer to convert forest are needed.

- ***Welfare poverty in colonization projects.*** Welfare poverty is not currently a major issue in the colonization projects studied. However, if farmers exhaust forests without simultaneously modernizing agricultural practices or diversifying to off-farm activities or both, incomes will fall and poverty may increase. Some farmers, particularly in the early stages of settlement of forested lands, do suffer from severe poverty and must deforest in order to plant annual crops to eke out a living; some of these fail, sell their land, and leave. Farmers settling now have more options than their counterparts two decades ago—development in and around projects means greater access to markets of all kinds—but pockets of poverty persist. This suggests the need for changes over time in policy tools put in place to support small-scale settlement activities.
- ***Investment poverty in colonization projects.*** Although food secure, some farm households are too poor to make the investments required to shift toward more land-intensive yet agronomically and economically viable agricultural activities. This is especially true of new arrivals during the early stages of colonization. However, unless the value of forests to smallholders is greatly increased, such investments, even if made, are not likely to halt deforestation. And if investments increase the cash flow available to hire labor, or farmers favor labor-saving technologies, it may even speed it up. Descriptive analysis as well as regression results point to important opportunities for trading scarce inputs locally to ease some resource constraints, enabling more farmers to improve their livelihoods via investment.
- ***A lasting role for smallholders already in the Amazon Basin?*** The 1995/96 Agricultural Census found 750,000 farm establishments of 100 hectares or less in the Amazon region. Brazil-wide trends of an aging and urbanizing population are felt in the Amazon, but influxes of new migrants in search of land, while not at levels seen in earlier decades, are an important countervailing force. Where small-scale farmers who choose to move on go (to cities, elsewhere in projects, or out along the receding forest margin) has serious poverty, growth, and environmental consequences. Who replaces them does, too. Current trends suggest that some remaining smallholders are expanding their holdings, while others are reducing theirs; some households are diversifying into urban activities (or are urban-based entrepreneurs diversifying into agriculture); and some with large holdings are consolidating land. A large majority of current landowners acquired their land from others; only about 20 percent of 1996 owners were the first occupants or owners of their farms.

The environmental and poverty consequences of a wholesale replacement of smallholders with large farm enterprises would be dire, with economic consequences not fully understood. This wholesale replacement is most likely to occur in Rondônia, along major overland transport routes, where soil and topographical characteristics are conducive to mechanized soybean production. Displaced, well-capitalized smallholders who move closer to the forest margins will deforest more quickly than their poorer counterparts migrating from other areas.

- ***A potential wave of new migrants?*** For the sizable Brazilian population below the poverty line, small-scale agriculture in the Amazon may be more profitable

than rural or urban opportunities outside the region. Major economic shocks, such as the major currency devaluations of the late 1990s, could make the returns to agriculture even more attractive. Financial incentives for migrating from other regions to the western Brazilian Amazon still exist, but policy incentives to migrate into forested areas with no private owner have been greatly reduced. Still, recent settlement programs as part of land reform have attracted new migrants to the area, and regional integration may reduce relocation costs of potential migrants. The altered population densities could place new pressure on forests or facilitate adoption of labor-using technologies and land uses, depending on shifting relative price situations.

- ***Increases in person/land ratios.*** Population increases coupled with reductions in the amount of land not under some claim (private holding, forest reserve, or other) are generating increasing person/land ratios in rural areas. If this process is slow and if technologies and investment capital are available, intensification of agricultural and extractive activities might begin. However, any major rapid influx that drastically shifts population density upward in areas where land is still legally available will increase pressure on privately held lands and designated reserves. In addition, if labor (especially adult male labor) were suddenly more abundant—if the borders with countries rimming the Amazon were opened, for instance—deforestation would increase. Put another way, labor-led intensification of agricultural activities (in the longer term, the ideal development path for the region) is not likely to be initiated by large, rapid population inflows, except under specific relative price scenarios not thought to be realistic or persistent. Even then, other factors facili-

tating quicker conversion from one land use to another than is the case under current practices would be needed; the more likely scenario is that farmers' land use strategies will adapt slowly to changes in factor availability.

Specific Agricultural and Extractive Activities

- ***Livestock production systems.*** Smallholder cattle production systems (dual-purpose systems oriented to dairy) are on the rise in the study area, because they can fulfill multiple objectives of smallholders (profitability, liquidity, food security, and risk avoidance) simultaneously. New technologies can dramatically improve the productivity and profitability of these systems, despite some nutrient-poor soils and difficult access to markets, but even the most labor intensive of the currently proposed systems does not change the likely pattern of complete deforestation. These systems require improvements in farm management practices to levels uncommon in the area, and they involve substantial up-front investments difficult to obtain, given current capital markets. Improvements in cattle production systems to increase pasture stocking rates without increasing desired herd size might be hampered by trends in agricultural research efforts in the region that are moving toward a more explicit focus on agroforestry. What's more, much public and private research on livestock has targeted technology for the medium-to-large landholder, so even existing technologies may not be appropriate for or accessible to the smallholder.
- ***Agroforestry systems.*** Some smallholder experimentation has begun in simple agroforestry systems involving fast-growing timber species and using profitable perennials or other crops as

“launching pads” for increasing the presence of woody perennials on farms. Other more complex systems involving tropical fruits are also the focus of much debate and hope. Financial analysis shows that these systems can be profitable, but because their labor needs place them beyond the reach of most smallholders, the markets for some products are not well established, and the investment may not begin to pay off for several years, these ventures are risky for smallholders. Moreover, because the labor required to establish and maintain these systems is so high, even if adopted, they will only occupy small areas of farms; hence, extensive land use systems, such as cattle ranching, will probably not be halted.

- ***Small-scale managed forests.*** Adding value to forests held by small-scale farmers is fundamental to slowing deforestation. Current legal restrictions on sustainable timber extraction from private forest reserves and bureaucratic obstacles to overcoming them are costly to farmers, whereas levels of enforcement and fines are low. Hence, farmers have every reason to disobey these restrictions. If restrictions could be implemented, farmer incomes would drop appreciably. Forestry policy that effectively prohibits the extraction of timber products by small-scale farmers from the 50 percent of their holdings reserved as forest should be reviewed and modified. However, important institutional investments (in timber extraction monitoring and verification systems, for instance) will need to be made to ensure that the extraction of timber products is done sustainably.

Increasing the value of nontimber forest products (NTFP) should also help protect remaining forests but probably less so than allowing sustainable timber ex-

traction. For example, a simulation using a bioeconomic model that doubled the 1994 farm-gate price of Brazil nuts predicted an 8 percent increase in forested area retained on a typical farm. Expanding and improving markets for particular NTFP to increase profitability will be challenging; policy efforts should focus on improving information exchanges on products, product quality, and product prices, and on identifying gaps in marketing and management skills along NTFP market chains and filling them. Note that making the forest more profitable through NTFP or timber extraction in the absence of effective monitoring could mean more damage to standing forests: profitability may encourage development or practice of unsustainable or excessively damaging extraction techniques. Finally, the emerging market for carbon offsets may play an important role in increasing the value of standing forest to smallholders. Research is needed to identify effective, self-enforcing, and self-financing monitoring mechanisms for all schemes aiming to increase forest value; the challenge is particularly complex for carbon markets. Cost-effective mechanisms are needed for linking carbon emitters (often in developed countries) with small-scale farmers (those retaining or sequestering carbon).

Policy Instruments, Policy Targets, and Policy Implementation

- ***Land tenure.*** Security of land tenure affects smallholder land use via access to information, extension services, and especially formal credit, and not via threat of expropriation. Speeding up formal processes of securing land tenure will likely increase the rate of smallholder deforestation, as access to credit becomes easier.

- **Infrastructure improvements.** Reducing transport time to markets generally will increase deforestation, but reducing seasonal fluctuations in transport time will not affect deforestation or use of cleared land. The diversity of types of traffic on rural roads—including vehicles specifically linked to marketing of output (such as milk trucks)—may have a greater impact on land use, and perhaps on deforestation, than road surfaces per se. Diversity of vehicles also may be a more important indicator of isolation (and possible food insecurity) than is sheer distance or time to market. Policymakers aiming to support markets for perennial tree crops should focus on increasing truck and bus traffic on rural roads; reviewing and revising the monopoly status of some bus and truck routes would be an important step in this direction.
- **Carbon payment schemes.** Paying small-scale farmers to retain forest (and the array of ecological services it can provide, especially carbon sequestration) will reduce deforestation rates, but since agriculture is profitable in these areas, the costs to policymakers in the aggregate will be high. More important, using small-scale farmers to preserve forest may be less efficient than doing so through extractive reserves or large-farm enterprises, since transaction costs in these cases may be lower. Tapping local organizations as a means of reducing transactions costs should be explored.
- **Land use zoning.** Locating farms on better versus poorer soils will only marginally slow deforestation rates and alter patterns of use of cleared land. Farmers on more fertile soils will earn much higher incomes than those located on poorer soils, but incomes of the latter group will still be sufficient to induce settlement. Establishing zones on the

basis of land quality will be difficult in practice in the western Brazilian Amazon because soils vary greatly within broad soil classes and even on farms. Certain characteristics of farms other than fertility—slope, degree of waterlogging, and rockiness—may matter more in dictating particular land uses, and the land use chosen may determine whether or not forests fall.

- **Government as actor.** Public services, especially in health and education, are being reduced in these rural areas, with possible negative consequences for human welfare. Families are torn between the desire to retain their claim to land and to farm it and the need to secure a reasonable education for their children. The incentives for and the capacity of local organizations or the private sector to completely fill the void left by retreating government programs are lacking. Reductions in educational and health services are leading to age-specific rural-to-urban migration, which may further reduce the household labor available for perennial tree crops and agroforestry production systems, thus fueling increases in demand for pasture to support extensive livestock production.

Relevance for Other Forest Margins Settings

- **Agroecological zones and economic conditions.** Soils in the western Brazilian Amazon are poor, labor is scarce, the potential for intensive forest extractive activities is limited by the low natural occurrence of commercially valuable products, and storage and transportation costs for all products are huge. These factors characterize many forest margins areas in Latin America (and more generally) and are found to influence deforestation rates and patterns of use of cleared land. This suggests that more

aggregate studies focusing on market analysis alone might leave out important elements of land use at the fringes of markets in other developing-country settings as well. That said, the specific findings must also be placed in their proper overall economic and agronomic contexts. Regional demand is growing and links to markets are expanding, along with profit opportunities, in the sites studied here. Rainfall patterns are at the edge of what other analyses have suggested might be viable for agriculture, at least under currently available technologies (see, for example, Chomitz and Thomas 2000). There is evidence here that expanding urban opportunities does take pressure off the forest. Differences in critical economic factors could change some important results.

- **Ranges of factor endowments.** Population densities in rural areas are quite low by conventional measurement (for example, as low as 3 individuals per square kilometer for the state of Acre), but if policy efforts to reduce access to forest areas are successful, person/land ratios will increase, leaving them more in line with other areas in Brazil and in the developing world (for example, 33 persons per square kilometer in the medium-density areas of Cameroon). Policymakers should be aware of such dramatic potential declines in land availability and look outside their borders for clues on how to manage this transition in ways that protect the forest and sustain livelihoods.
- **Policy setting.** The western Brazilian Amazon is a frontier area, with study sites characterized by the general absence of strong government, lack of ef-

fective policy instruments, incomplete knowledge regarding the natural resource base and its possible uses, high transportation costs, and the predominance of private property, especially among smallholders. The importance of communally based resource management, the length of time forest margin areas have been inhabited, and the distance to markets can be expected to alter the outcomes of policy/technology changes on land use vis-à-vis those presented here.

In this report, which examines the potential for achieving the three “critical triangle” development objectives—environmental sustainability, economic growth, and poverty alleviation—in the agroecological and socioeconomic context of colonization projects at the southern edge of the western Brazilian Amazon, no recipe for success was discovered, no plan for saving the Amazon was unveiled, and neither was expected. Rather, trade-offs among some of the critical triangle’s objectives were identified, and the policy, technology, and institutional changes required to effect these changes were explored. Sustainable intensification of agriculture without continued deforestation may be possible in the Amazon, but so far, the economic and policy incentives for doing so are not in place, and the technological base and marketing infrastructure to support such a development path are also lacking. Research and policy action can increase the chances for sustainable intensification, but large investments and strengthened political will are required. Since intensifying agricultural land use will not remove pressure from remaining forest, a mix of regulations and incentives are needed to either increase the value of standing forest or increase encroachment costs, or both.

APPENDIX A

Regression Variable Statistics and Comprehensive Regression Results

This technical appendix contains a comprehensive set of descriptive statistics for variables used in the regression analysis, and a complete set of results from that analysis.

Table A.1 describes and presents the variables included in the regression analyses, along with several reference variables that help establish farm and farm household characteristics. Note that all land use variables are expressed as proportions of total farm size. Descriptive statistics are arranged as follows: dependent variables (the proportion of farmland held in different land uses in 1996); lagged dependent variables (the proportion of farmland held in different land uses in 1994); S_{t-2}^i status of land when the farmer arrived on it, $Z_{t-\Delta}^i$ (recall that “ $t-\Delta$ ” is the year of arrival of the farmer interviewed in 1996 on the lot); farm characteristics relevant for different time periods (tenure upon arrival, $Z_{t-\Delta}^{TN}$; tenure in 1996, Z_t^{TN} ; farm resource endowments, Z^N ; transportation, Z^{TR} ; other farm characteristics, Z^P); community characteristics (local organizations, Z^{COM} ; transportation, Z^{TR}); and farmer and household characteristics (origin of household head, Z^H ; migratory history, $Z_{t-\Delta}^H$; household assets upon arrival, $Z_{t-\Delta}^A$; and other characteristics of household heads, Z^H). Units of measure, sample means, standard deviations, and ranges are provided for all variables.

In Table A.2, time is segmented as follows: $t = 0$ refers to the year the lot was officially made available for agriculture, $t < arr$ refers to time prior to a farmer’s arrival in the region, $t < arr$ in project refers to time prior to arrival of a farmer in the project but after arrival in the region, $t < arr$ in lot refers to time prior to arrival on a farmer’s lot but after arrival in the colonization project; $t = arrival$ refers to time of a farmer’s arrival on his/her lot; $t = 1994$ and $t = 1996$ refer to calendar years 1994 and 1996, respectively; $t = 1994-96$ refers to the two-year period between 1994 and 1996, $t = arr$ to 1996 refers to the time elapsed between arrival of a farmer on a lot and the 1996 cropping year; and all t is a label used for time-insensitive variables (such as soil quality).

Table A.2 contains a complete set of results of the regression analysis. Results of F-tests specific to blocks of variables appear (in bold) in Table A.2. The order of presentation of blocks of variables highlights the role of multivariate analysis vis-à-vis other empirical techniques used in this report in testing land use hypotheses: farmer characteristics beyond those captured in the bioeconomic model are presented first, followed by human and financial resources upon arrival that are important initial conditions in the linear programming model.

Table A.1 Descriptive statistics for variables used in the regression analysis

Variable description	Unit	Mean	Standard deviation	Range
Land use				
1995/96 agricultural year		Dependent variables		
Total farm size*	Hectares	83	47	24–254
Open*	Proportion ^a	.47	.23	.10–1
Secondary forest	Proportion	.05	.06	0–.28
Annuals, alone	Proportion	.03	.04	0–.15
Pasture ^b	Proportion	.31	.19	0–.82
Perennials, alone	Proportion	.05	.07	0–.31
Annuals and perennials	Proportion	.03	.04	0–.20
Agroforestry systems* ^c	Proportion	.01	2.6e–2	0–.14
Home garden*	Proportion	4.2e–3	6.2e–3	0–.03
Remaining forest	Proportion	.53	.23	0–.90
1993/94 agricultural year		s_{t-2}ⁱ variables		
Total farm size*	Hectares	79	49	20–360
Open*	Proportion	.40	.21	.01–1
Secondary forest	Proportion	.07	.07	0–.31
Annuals, alone	Proportion	.07	.05	0–.24
Pastured*	Proportion	.22	.18	0–.72
Perennials, alone	Proportion	.04	.06	0–.26
Annuals and perennials	Proportion	.01	.03	0–.20
Remaining forest ^c	Proportion	.60	.21	0–.99
State of land upon arrival of 1996 owner		Z_{t-Δ}^S variables		
Total farm size	Hectares	71	34	2–213
Open	Proportion	.11	.18	0–.90
Secondary forest*	Proportion	.01	.10	0–.67
Annuals*	Proportion	2.4e–3	1.1e–2	0–.08
Pasture*	Proportion	3.8e–2	.11	0–.71
Perennials*	Proportion	.01	2.7e–2	0–.15
Agroforestry systems*	Proportion	1.5e–3	.01	0–.14
Home garden*	Proportion	9.7e–4	3.8e–3	0–.02
Remaining forest	Proportion	.89	.18	.10–1
Presence of pasture investments upon arrival	Yes=1	.15	.35	0–1
Changes in farm size since arrival				
Land sold since arrival	Hectares	–.58	3.33	–24–0
Land purchased since arrival	Hectares	12.40	29.10	0–130
Farm characteristics				
Tenure upon arrival		Z_{t-Δ}^{TN} variables		
Received from INCRA ⁺	Yes=1	.20	.40	0–1
Bought or traded	Yes=1	.74	.44	0–1
Acquired lots from INCRA or via purchase/trade	Yes=1	.06	.24	0–1
Tenure in 1996 ^f		Z_t^{TN} variables		
Documentation of presence ⁺	Yes=1	.30	.46	0–1
Definitive title	Yes=1	.70	.46	0–1
Document indicating purchase of land by current owner	Yes=1	.24	.43	0–1

(continued)

Table A.1—Continued

Variable description	Unit	Mean	Standard deviation	Range
Farm characteristics (continued)				
Farm resource endowments		Z_t^N variables		
Water, year round	Yes=1	.88	.33	0–1
Land quality, one restriction				
Best soil, little limitation	Yes=1	.06	.24	0–1
Low fertility	Yes=1	.21	.41	0–1
Land quality, multiple restrictions ^{g+}	Yes=1			0–1
Land quality, waterlogging	Yes=1	.03	.17	0–1
Land quality, severe slope	Yes=1	.26	.44	0–1
Transportation		Z_t^{TR} variables		
Time to market, dry season	Minutes	132	81	9–420
Ratio of time to market (rainy season/dry season)	–	2.3	4.8	1–48
Other farm characteristics		Variable and project dummy Z^P		
Lot opening date	Year	1981	2.9	1973–94
Location of lot (Project — PP/AC or Theo/RO)	1=Theo	.53	.50	0–1
Community characteristics and market access				
Local organizations		Z^{COM} variables		
Farmers' associations	Yes=1	.95	.22	0–1
Evangelical church ^h	Yes=1	.74	.44	0–1
Government-sponsored union	Yes=1	.36	.48	0–1
Transportation ⁱ		Z_t^{TR} variables		
Number of types of vehicles on the road, dry season	Modes	1.6	1.0	0–4
Seasonal change in number of modes (dry – rainy)	Modes	0.4	0.7	0–3
Flow of vehicles, most frequent, dry season	Number/month	32.0	42.0	0–210
Farmer and household characteristics				
Origin of head of household		Z^H variables		
Raised in North ⁺	Yes=1	.22	.42	0–1
Raised in Central West	Yes=1	.05	.22	0–1
Raised in Northeast	Yes=1	.11	.32	0–1
Raised in Southeast	Yes=1	.41	.49	0–1
Raised in South	Yes=1	.21	.41	0–1
Migration history		Z_{t-Δ}^H variables		
Number of states passed through	Number	1.30	0.80	0–3
Urban experience	Yes=1	.44	.50	0–1
Moved directly to lot upon arrival	Yes=1	.67	.47	0–1
Lived with friend/relative upon arrival ⁺	Yes=1	.25	.44	0–1
Worked on a <i>fazenda</i> upon arrival	Yes=1	.08	.28	0–1
Number of moves within project	Number	.19	.49	0–1
Date 1996 farmer arrived on lot	Year	1987	4.8	1973–96
Household endowment upon arrival		Z_{t-Δ}^A variables		
Resources brought	Months	4.50	5.30	0–18
Household size upon arrival	Number of people	5.06	2.85	1–15
Proportion of adults upon arrival	Proportion	.70	.25	.27 – 1
Steady off-farm income source	Yes=1	.04	.20	0–1

(continued)

Table A.1—Continued

Variable description	Unit	Mean	Standard deviation	Range
Farmer and household characteristics (continued)				
Household endowment upon x arrival year of arrival, interactive terms				
Resources brought x arrival year	...			
Household adults x arrival year	...			
Household children x arrival year	...			
Steady off-farm income x arrival year	...			
Other characteristics of head of household		Z^H variables		
Literacy (read and write)	Yes=1	.33	.47	0–1
Ownership unchanged (1994–96)	Yes=1	.94	.24	0–1
Nonresident owner, managed by tenant	Yes=1	.02	.14	0–1

Notes: INCRA is the Instituto Nacional de Colonização Reforma Agraria. PP/AC is Pedro Peixoto, Acre, and Theo/R is Theobroma, Rondônia, the sites studied here. A *fazenda* is a large-scale cattle ranch. “Months” indicates the length of time that resources farmers brought with them would last.

* Indicates variables included here for reference purposes only. They do not appear in the regressions.

+ Indicates reference variables (omitted from blocks in the regressions).

^a Indicates proportion of total operational holding in that land use for the indicated year.

^b Includes area intercropped with annuals and first-year pasture (sensitivity analysis on treatment of intercropped area in regressions suggested this grouping).

^c Agroforestry systems, usually intercropped with perennials, are considered perennials for purposes of comparability with 1994 data.

^d A high negative correlation with proportion of farm remaining in forest in 1994 prevents inclusion of both variables; other results are robust if this variable is substituted for 1994 forest proportion in the equations.

^e Calculated assuming the same size home garden in 1996 existed in 1994 for purposes of comparability with 1996 data (this difference is usually slight but should give a more accurate picture of standing forest area in 1994).

^f For approximately nine cases, titling situation of the land was not known; missing values estimated based on the larger sample—a logit with dependent variable 1996 tenure situation (successfully categorizing 85 percent of valid cases).

^g Fertility and rockiness, sometimes with slight slope.

^h Every road sampled contained a Catholic Church.

ⁱ This variable is reported at household level but refers to passage of vehicles along the road in front of the farm.

Table A.2 Factors Influencing land use, Tobit estimates and block F-tests

Variable description	Variable labels	Dependent variables					
		Forest	Pasture	Annual crops	Fallow	Annual perennial intercrops	Perennial crops
Farmer characteristics							
Origin of household head (t<arrival)	Block F-test	1.00	2.76**	1.45	0.31	2.21*	1.14
	Central-West	0.05	-0.08	0.03	0.00	-0.01	0.02
	Northeast	0.05	-0.01	-0.02	0.01	0.02	-0.04
	Southeast	-2.59E-03	0.03	2.62E-04	0.02	-0.06*	-0.04
	South	0.03	-0.05	0.03	-0.01	-0.05	-0.03
Migration history (t<arrival in project)	Block F-test	4.41**	3.63**	1.20	0.05	7.96***	5.45***
	Urban experience	0.06***	-0.05***	0.02	-0.01	-0.01	-0.05***
	Number of states visited	-0.01	0.01	-2.02E-04	-1.99E-03	0.06***	0.00
(t<arrival in lot)	Block F-test	1.61	0.42	1.91	0.10	4.16*	2.77*
	Direct to lot	-0.02	0.02	0.03**	-0.01	-0.05**	-0.02
	Ranch experience	-0.03	0.04	0.01	0.00	-0.18***	-0.03
	Number of within project moves	0.04*	1.33E-03	-1.99E-03	-0.01	2.80E-04	-.04***
Literacy (t<arrival)	Household head literate	-0.02	0.03*	-0.04***	0.02	0.01	0.04**
Human and financial resources							
(t=arrival)	Arrival date	-0.01*	4.37E-03	-2.21E-05	2.76E-03	0.01***	-1.32E-03
	Block F-test	2.29*	4.38***	2.32*	0.43	4.27***	2.19*
	Resources brought	0.01**	-2.81E-03	1.42E-03	-1.26E-03	-9.00E-04	-1.85E-03
	Off-farm income	0.01	-0.02	-0.03	0.03	0.14***	0.02
	Household size	1.91E-03	-0.01***	1.78E-03	1.44E-03	0.00	0.01**
	Proportion adults	0.09**	-0.13***	-0.03	-0.03	0.11***	0.06**
Farm characteristics							
Land status							
(t=0)	Lot opening date	-0.01*	0.01*	-8.26E-04	0.00	0.00	0.01
Land tenure							
(t=arrival)	Block F-test	6.20***	6.17***	0.06	0.08	1.30	0.08
	Bought/traded	2.08E-03	0.01	2.94E-03	8.01E-04	-0.03	0.00
	INCRA and other	-0.19***	0.17***	-0.01	0.02	-0.10	0.02
(t=1996)	Block F-test	1.51	8.99***	1.54	0.46	5.41***	1.23
	Definitive title	-0.04	0.08***	-0.01	-0.02	0.07***	-0.03
	Purchase document	0.03	-0.06**	0.02*	-0.01	0.05**	-0.01
Management							
(t=1994-96)	Block F-test	0.09	0.00	0.39	0.07	7.47***	0.33
	Ownership change	-0.01	-2.23E-03	0.01	0.02	0.19***	-0.02
(t=1996)	Tenant managed	0.02	-2.01E-03	-0.02	0.02	0.02	-0.04
Collective action availability							
(t=1996)	Block F-test	2.54*	5.64***	3.49**	0.53	1.27	3.78**
	Farmers' association	0.01	0.07	-0.06**	-0.04	0.01	-0.05
	Evangelical church	3.91E-03	0.03	-0.03**	0.01	0.01	-0.04**
	Labor union	-0.06**	0.10***	-0.03***	-0.02	0.05*	0.02
(t=arrival to 1996)	Block F-test	1.72	0.06	6.22***	0.02	0.75	0.10
	Land sold	-1.03E-03	-6.09E-04	-7.89E-05	-5.48E-04	-1.50E-03	8.41E-04
	Land purchased	8.62E-04**	1.02E-04	-8.43E-04***	-5.08E-05	-5.11E-04	8.55E-05

(continued)

Table A.2—Continued

Variable description	Variable labels	Dependent variables					
		Forest	Pasture	Annual crops	Fallow	Annual perennial intercrop	Perennial crops
Farm characteristics (continued)							
Land quality (all t)	Block F-test	1.52	4.55***	2.00*	1.35	3.98***	4.85***
	Year-round water	0.01	0.01	-0.04***	0.03	0.05**	-0.06***
	Best soil	-4.50E-03	0.07	-0.02	-0.11**	-0.11***	0.11***
	Low fertility	-0.06**	0.10***	0.01	-0.04	0.02	-0.03
	Waterlogging	5.96E-04	0.13**	-0.03	-0.03	-0.29	-0.04
	Severe slope	-0.06***	0.09***	-2.52E-03	0.04	-0.05***	-0.01
	Block F-test	5.41***	12.00***	0.95	1.06	7.91***	1.58
(t=arrival)	Farm size	-9.65E-04***	1.42E-03***	2.94E-04	4.84E-05	-1.87E-03***	-5.48E-05
	Proportion cleared	-0.21**	0.23***	-0.02	-0.13*	3.43E-03	0.12**
	Pasture investments	0.03	-0.01	-0.01	0.02	-0.04*	-0.01
	Block F-test	31.17***	35.29***	3.34**	4.16***	6.03***	5.59***
(t=1994)	Proportion forest, 1994	0.78***	-0.69**	-0.10**	-0.03	0.09	0.07
	Proportion perennial, 1994	0.44**	-1.05***	0.01	0.49**	0.26	0.12
	Proportion annuals, 1994	-0.56**	0.44**	0.15	0.01	-0.28*	0.19
	Proportion annual/perennial, 1994	-0.25	-0.20	-0.40**	-0.09	1.04***	1.29***
	Proportion fallow, 1994	0.37**	-0.82***	-0.01	0.46***	0.19	0.08
Transport Costs (t=1996)	Block F-test	1.66	4.57***	0.61	1.99*	4.39***	3.07**
	Time to market	2.60E-04*	-2.32E-04*	-3.16E-05	1.42E-04	-5.26E-05	-1.36E-04
	Rainy/dry ratio	-1.38E-03	2.22E-03	6.51E-04	5.67E-04	1.05E-03	-3.27E-04
	Number of types of vehicles	-1.91E-03	-0.02**	-3.88E-03	3.81E-03	0.02***	0.02***
	Seasonal change in # of types of vehicles	0.03*	-0.03*	0.01*	0.00	-0.01	0.00
	Flow of vehicles	1.84E-04	-4.94E-04**	1.01E-04	7.06E-04***	5.18E-04***	-5.95E-04***
Project dummy		-0.14***	0.12***	-0.02	-0.05	0.07*	0.05**
Constant		33.45***	-26.42***	1.87	-1.77	-20.75*	-8.63
Chi-squared (46)		219***	211***	62*	46	133***	95***
N		96	96	96	96	96	96

Note: Bold type indicates results of F-tests.

* Statistically significant at the 10 percent level.

** Statistically significant at the 5 percent level.

*** Statistically significant at the 1 percent level.

Likewise, in the farm characteristics block, we first examine the impacts of land status, land tenure, land management schemes, and collective action (outside the framework of the bioeconomic model) on

land use patterns, before moving on to examine the roles of land quality and other farm characteristics, since these, too, are explicitly included in the bioeconomic model.

APPENDIX B

The Farm-Level Bioeconomic Model

This appendix algebraically describes the structure of the farm-level bioeconomic model used to generate the policy and technology simulations presented in the body of this research report. Detailed footnotes in this appendix are used to explain how the general model is modified to reflect the objectives of, and constraints faced by, a particular set of small-scale agriculturalists in the western Brazilian Amazon. Definitions of indices, variables (all in capital letters), and technical coefficients important to understanding the equations appear in Tables B.1, B.2, and B.3.

The bioeconomic linear programming (LP) model maximizes the net present value of consumption over a 25-year planning horizon.^{78,79} Revenues are generated from the sale of milk, beef cattle, calves, food grains, Brazil nuts, coffee, bananas, and family labor.^{80,81} These revenues minus production and transportation expenditures become available to reinvest on the farm or to satisfy the family's consumption needs. The farm household chooses the intertemporal allocation of savings (S) and consumption (D) that maximizes its utility (U) over the planning horizon; t indexes years (1 to 25) and p indexes seasons (1 = dry season, 2 = wet season).

Profits ($\Pi_{p,t}$) are the revenues minus production costs and expenditures on basic food/clothing and agricultural equipment.⁸² $D_{p,t}$ is thus the consumption of nonessential goods

⁷⁸Technically, the model operates on a 15-year planning horizon. To extend the time horizon to 25 years, and to simultaneously avoid the pitfalls associated with terminal conditions, the model is first run for 15 years, the solution for year 5 is extracted, the model is rerun using year-5 solutions as the "starting points" for the second 15-year run, and so on, until a 25-year horizon is reached, which requires 5 runs of the 15-year model.

⁷⁹Baseline and other simulations presented in this report use a 9 percent discount rate, constant 1992/93 prices over the entire planning horizon (unless otherwise stated), and initial conditions for selected farm types based on field survey data and presented in Table 4.1 of the main text. Sensitivity analyses based on alternative price scenarios, different discount rates and other key parameters were performed and the results are summarized in Chapter 4.

⁸⁰Revenues from the sale of household labor are restricted in all simulations. Hiring out of family labor and hiring in daily labor in the baseline are each restricted to 15 person-days per month. Other baseline restrictions on input and output transactions are the absence of credit and a 50 liters per day limit on daily milk sales.

⁸¹Neither production risk (related to weather and pest shocks, for example) nor price risk is included in the model. Inclusion of either would be expected to increase resources dedicated to annual crop and livestock production, which, in turn, would likely increase deforestation. However, inclusion of other sources of risk (for example, human health risk) may have profound effects on both deforestation and use of cleared land.

⁸²Receipts from sales are net of transportation costs, which vary by season and mode of transport, and include family labor. For example, grain transported by truck to market costs R\$91 per round trip, as estimated from 1996 field data and adjusted to 1993 prices.

Table B.1 Important indexes in the bioeconomic linear programming model

Indexes	Description	Element
0	Initial value	Initial value at year $t = 0$
a	Livestock type	a1, milking cows a2, beef cattle
c	Costs of activities	c1, seasonal livestock cost c2, other monthly costs
h	Trips to market	h1, using oxen h2, using trucks
m	Months	m1, May m2, June ... m12, April
o	Levels of soil nutrients Deficiency	o1, first level o2, second level o3, third level (refer to Figure B.1)
p	Seasons	p1, dry season p2, wet season
pr	Products	pr1= rice; pr2 = corn; pr3 = beans; pr4= manioc; pr5 = coffee; pr6 = bananas; pr7= <i>brizantão</i> ; and pr8 = kudzu
r	Rotations	r1, rice and corn intercropped followed by beans r2, rice in monoculture followed by beans r3, corn in monoculture followed by beans r4, manioc r5, coffee with corn and beans the first 2 years r6, pure stand of bananas r7, pasture <i>brizantão</i> r8, pasture <i>brizantão</i> with the legume kudzu
t,T	Planning horizon	t1 to t25 (in agricultural years), "T" denotes the final year of the planning horizon
v	Technologies	v1, low-level, commonly observed in the study area v2, intermediate level v3, high-level, practices recommended by Embrapa
y	Vintage	y1 to y20 (in years), to track the ages of animals, rotations, and so on
x	Extractive products	x1, Brazil nuts x2, timber

and services such as extra food, extra clothing, educational services, televisions, cars, parabolic antennas, and so on. Savings (S_{pt}) can be accumulated. The maximization is subject to economic/factor constraints and agronomic/environmental constraints.

$$\text{MAX } U = \sum_{p=1}^2 \sum_{t=1}^{25} \frac{D_{p,t}}{(1+i)^t} = \sum_{p=1}^2 \sum_{t=1}^{25} \frac{\Pi_{p,t} - S_{p,t}}{(1+i)^t} \quad (1)$$

Tables B.1, B.2, and B.3 provide labels and brief descriptions of indexes, variables, and technical coefficients that will be useful

references for the material presented in the remainder of this appendix.

Economic Restrictions

The following economic restrictions are placed on the farm household's maximization problem.

Cash in hand in any season p plus credit taken in the first season of year t must meet minimum family expenses, loan repayment,

Table B.2 Relevant variables in the bioeconomic linear programming model

Variable	Description	Unit of measure
Π_{pt}	Profits	R\$/season
A_{ayvpt}	Livestock	head/season
CF_{yvt}	Cleared forest	hectare/year
D_{pt}	Consumption	R\$/season
E_t	Total indebtedness	R\$/year
F_{yt}	Fallow (y1 to y6) and primary forest (y7)	hectare/year
H_{hmt}	Trips to market	trip/month
J_{prmt}	Stocks of foodgrains	kg/month
JB_{prmt}	Foodgrain purchases	kg/month
JS_{prmt}	Foodgrain sales	kg/month
K_{pt}	Cash balances	R\$/season
KB_t	Borrowed cash	R\$/year
LH_{mt}	Labor hired in (adult males only, md = man-days)	md/month
LS_{mt}	Household labor sold off farm (adult males only)	md/month
LT_{mt}	Labor transferred among activities (adult males only)	md/month
ND_t	Nutrient deficiencies in cleared areas	kg/year
NO_t	Stocks of nutrients in cleared areas	kg/year
NOF_t	Stocks of nutrients in forested areas	kg/year
P_{prmt}	Production (summed over each rotation)	kg/month
R_{ryvt}	Land in particular rotations	hectare/year
S_{pt}	Savings	R\$/season
Land agronomically available for but not used in:		
SA_t	Annuals	hectare/year
SPE_t	Perennials	hectare/year
SF_t	Forest (secondary forest/fallow)	hectare/year
SP_t	Pasture	hectare/year
SR_t	Rehabilitated pasture	hectare/year
U_{pt}	Value of the objective function	R\$ (discounted)
X_{xmt}	Extractive activities: x1 (Brazil nuts); x2 (timber products)	20 kg/month m ³ /month
W_{yt}	Rehabilitating pasture land	hectare/year
Z_{prmt}	Short-term foodgrain loans	kg/month

and costs of purchases of agricultural inputs, including hired-in labor.^{83,84}

$$\begin{aligned}
 K_{pt} + KB_{pt} \geq & mk_p + (k + e) E_{pt} + e E_{p=2T} + c_{e=1p} A_{ayvpt} \\
 & + \sum_r \sum_y \sum_v \sum_{mep} C_{e=2yvmt} (R_{ryvt} + F_{yt} + H_{hmt} \\
 & + X_{xmt}) + \sum_{mep} wage_m LH_{mt}
 \end{aligned} \tag{2}$$

Farm-households have access to family and off-farm labor, and the former is divided into “adult male” and “other” categories. Adult males can perform all tasks, and are most efficient at them. Other household laborers include females,

⁸³The dry season comprises five months (May to September) and the wet season seven months; cash is fungible across months within seasons, but not across seasons.

⁸⁴For all simulations, food expenses are composed of fixed and variable components, while living expenses (for example, sugar, cooking oil, and basic clothes and tools such as hoes, plows, and seeders) are fixed and independent of household size or composition. Fixed food and living expenses are set at R\$118 per month, and are treated as seasonal in nature, that is, expenses can be “smoothed” across months within seasons, as long as total cash available to cover them is R\$590 = R\$118 times 5 dry-season months (or R\$826 = R\$118 times 7 rainy-season months) or more. Variable production and labor costs are a fixed proportion of the level and type of activities available to farmers. Costs of producing annual and perennial crops are composed mainly of seeds, bags, and transportation costs. Primary livestock costs are fences, animal replacements (mortality rates are nonzero), and health and sanitary costs.

Table B.3 Technical coefficients in the bioeconomic linear programming model

Variable	Description	Unit of measure
mk_p	Minimum seasonal expenses for fixed costs and some food and family items	R\$/season
i	Discount rate	%/year
c_{cp}	Variable production costs, by activity	R\$/season
k	Loan repayment rate	R\$/year
e	Interest rate on loan	%/year
lfm_m	Adult males in the family (md = man-days)	md/month
lfo_m	Other family members (expressed in adult equivalents)	md/month
lf_y	Adult male labor needed to clear one hectare of forest of age y	md/month
lxm_m	Adult male labor needed to extract timber (per hectare of forest)	md/month
lxo_m	Labor of any type needed to extract Brazil nuts (per hectare of forest)	md/month
la_{ayvp}	Labor of any type needed for herd management (by age of animal and technology)	md/month
lrm_{ryvm}	Adult male labor needed for crop production, by rotation, age, and technology ^a	md/month
lro_{ryvm}	Labor of any type needed for crop production, by rotation, age, and technology ^a	md/month
lh_m	Labor of any type required for marketing	md/trip
co_{prm}	Grain storage losses per crop	%/month
j_{prm}	Household foodgrain requirements per crop	kg/month
$jr_{pryv=1m}$	Seed requirements (for v1 technologies only) by rotation ^a	kg/month
q_{pr}	Farmgate prices by crop	R\$/unit
nd_{rv}	Yearly nutrient demand, by rotation and technology ^a	kg/year
yl_{rpyv}	Monthly yields, by rotation, age, and technology ^a	kg/year
nr_{prvo}	Nutrient deficiency response function, by rotation and product	proportion
nf_y	Nutrients released by slashing/burning the forest of age y ^a	kg/year
naf_y	Nutrients accumulated on fallow land of age y ^a	kg/year
$wage_m$	Daily rural wage	R\$/day
qa_{ayv}	Farmgate animal prices	R\$/1 head

^aper hectare.

children and the elderly, who cannot perform some tasks (for example, forest felling, pasture establishment, and timber extraction), and are less efficient than adult males in all tasks that they can perform, that is, their task-specific labor coefficients are smaller than those for adult males. Only adult males can be hired in, and only adult male family members can sell labor off farm.

Two constraints account for the specific type of labor needed to perform particular agricultural activities: one for activities that only adult males can perform (equation 3),

and a second (equation 4) for tasks that other household members can perform (though less efficiently than males). The switching function (variable LT) links the two constraint equations by allowing “excess” labor from the adult-male-only tasks to tasks that can be accomplished by anyone. Adult male labor can be sold off-farm and adult male additional labor can be hired on-farm at variable monthly wage rates, but both types of labor flows are limited in the model (to 15 man-days per month, unless otherwise indicated) due to labor market imperfections.

The monthly labor constraint for tasks performed by adult males only is⁸⁵

$$\begin{aligned} 1f_{m_t} + LH_{m_t} - LS_{m_t} - LT_{m_t} \\ \geq \sum_r \sum_y \sum_v 1r_{m_{ryvm}} R_{r>6yvt} \\ + \sum_y \sum_v 1f_{ym} CF_{yvt} + 1x_{m_t} X_{x=2mt} \end{aligned} \quad (3)$$

The monthly labor constraint for activities performed by any household member (measured in adult equivalents) is

$$\begin{aligned} 1f_{o_m} + LT_{m_t} \geq \sum_r \sum_y \sum_v 1r_{o_{r<7yvm}} R_{ryvt} \\ + \sum_a \sum_y \sum_v 1a_{ayvp} A_{ayvm=pt} \\ + 1x_{o_m} X_{x=1mt} + \sum_h 1h_m H_{hmt} \end{aligned} \quad (4)$$

The adult male equivalents for production activities varying by age and sex are presented in Table B.4.

Household food security can be ensured by growing the basic grains (rice, corn, and beans) and manioc needed to meet family nutrient intake requirements or by purchasing these foods in the market, either with available cash or by securing short-term loans to purchase food.⁸⁶ Food products (except milk and beef) can be stored for later consumption, to use as seed the following year, or to sell at a later date. (There is no milk or beef consumption minimum requirement). If stored grains are not sufficient to meet family needs, a short-term food loan (Z) can be taken in any month but

must be paid back at the end of the year at twice its original value:

$$J_{prmt} + Z_{prmt} \geq j_{prmt} \quad \forall pr < 7 \quad (5)$$

Stocks of foodgrains are subject to a monthly volumetric upper bound (based on average storage capacity identified by field research and defined in the initial conditions), and product-specific spoilage rates are applied. Manioc and beans store better than rice, and stored corn, which is especially susceptible to insects, rodents, and spoilage due to humidity, experiences a 30 percent yearly loss:

$$\begin{aligned} J_{prmt+1} = J_0 + c_{o_{prmt}} J_{prmt} + P_{prmt+1} \\ + JB_{prmt+1} + Z_{prmt+1} \\ - j_{prmt} - \sum_r \sum_v j_{r_{prv=1m}} R_{ryv=1t+1} \\ - JS_{prmt+1} \quad \forall pr < 7 \end{aligned} \quad (6)$$

In lieu of explicit treatment of risk in the model, Equation 7 requires households to maintain a minimum of R\$500 (in any season) in cash or quickly saleable assets such as grain stocks or livestock:

$$\begin{aligned} \sum_{m \in p} \sum_{pr < 7} q_{pr} J_{prmt} + \sum_y \sum_v q_a_{ayv} A_{ayvt} \\ + K_{pr} \geq 500 \end{aligned} \quad (7)$$

⁸⁵For the purposes of the baseline and other simulations appearing in this paper, the following information on labor supply, demand, and costs are relevant: family members cannot work more than 26.1 person-days during peak months and 21.7 during the off-peak months; chainsaw operators can be hired at R\$27 per day (R\$22 per day for the service plus R\$5 in operating costs-gas and oil); unskilled labor can be hired at R\$7 per day during May and June, R\$5.60 per day during other peak labor demand months, and R\$3.70 per day during the off-peak months; and again, no more than 15 person-days can be hired in or sold out in any month. Hired labor is 1.125 times more expensive to account for supervision costs.

⁸⁶For all simulations, monthly food consumption is equal to 15 kilograms of rice, 19.2 kilograms of corn (mainly to feed animals), 1.8 kilograms of beans, and 8.4 kilograms of manioc per adult equivalent and is drawn from field data. The archetypical household contains 4.29 adult equivalents, and household size and composition are constant over the planning horizon. Monthly household food consumption requirements, therefore, equal 4.29 times the numbers above for each product. Short-term consumer credit to meet food security needs can be taken out in any month. As much cash as necessary can be borrowed to meet food needs, but these loans must be repaid at twice their value by the end of the calendar year.

Table B.4 Adult male equivalents for production activities

Age group	Sex	Role	Male equivalent
0-4	M, F	Dependent	0.0
5-14	M, F	Agricultural and extractive activities	0.5
15-54	M	All activities including slash and burn and fence building	1.0
15-54	F	Agricultural and extractive activities	0.5
55-64	M	All activities including slash and burn and fence building	0.6
55-64	F	Agricultural and extractive activities	0.3
> 65	M, F	Dependent	0.0

Note: EMATER and Embrapa, personal communications.

Production credit can be taken in any year other than the last year of the planning horizon T ; total indebtedness at any point in time (E_t) cannot exceed R\$2,000, an initial condition of the model:

$$E_{t+1} = E_0 + (1 - k)E_t + KB_{t+1 \neq T} - E_{t+1=T} \quad (8)$$

Grain stocks can be sold in any month of the year, once monthly family nutritional requirements have been met. Transportation time and costs depend on the availability of transportation means (for example, car, bus, ox, and so forth), road infrastructure and distance to the market, as specified in the initial conditions (see Table 4.1). Households can also supplement their income by extracting timber (not permitted in the baseline simulation) and Brazil nuts or by selling adult male labor off-farm (again, up to the specified limit).

Agronomic Restrictions

One of the novelties of this LP model is the explicit treatment of several biophysical “realities” known to constrain product and technology choice in areas with nutrient-

poor and acidic soils.⁸⁷ These realities are introduced into the model in two ways: first, rotations and sequences of rotations (indexed by r) are restricted to particular types of land, where “type” refers to the characteristics of particular plots of land (for example, soil nutrient availability) that are determined in part by their previous uses, which the model “knows.” Second, yields for annuals, perennials, and pastures deteriorate over time (in product- and technology-specific ways) if they are cultivated on the same plots of land.

Land dedicated to a particular rotation can be maintained in that use, abandoned to fallow, or put to a set of other agronomically feasible uses. Land maintained in a given rotation grows “older” each year; this aging process is accounted for by the index y . Four rotational constraints capture the soil structure and weed invasion effects of continuous cropping in the region. The unidirectional arrows between land uses in Figure 2.2 are modeled using a set of “switching” variables that allow the model to switch land from more restrictive to less restrictive uses. For example, land planted to annual crops in one period can be switched to fallow, perennials, or to pasture

⁸⁷Some of these realities, such as restrictions on the types of cultivating practices one can follow, are deduced from field data and data collection activities. Yield loss coefficients are derived from farmer interviews and discussions with agronomists and soil scientists.

in the next period. As explained below, switches from less to more restrictive land uses are not allowed without accompanying investments. In addition, the model restricts land allocated to all land uses to the 60 hectares available on the model farmer's lot.

In any given year, area that is agronomically available for annual cropping can come from one of two sources (1) land allocated to annual cropping the previous year, or (2) recently cleared forest or fallow land (*CF*). If it is financially worthwhile, however, some of the land available for annual cropping could be allocated to one of three other uses (*SA*): perennials (with proper investments), fallow land, or pasture. So land actually allocated to annual cropping in a given year consists of the pool of agronomically available land for that purpose, less the land unallocated because of economic concerns:⁸⁸

$$\sum_r R_{r<4t} = \sum_r R_{r<4t-1} + CF_t - SA_t \quad (9)$$

Similarly, area agronomically available for perennial cropping in a given year consists of the previous year's perennial crops plus the area that could have been used for annual cropping, but wasn't (*SA*). From this agronomically suitable pool of land, again, only part might actually be allocated to this year's perennial crop, and part (*SPe*) to another use for which it is agronomically suitable (fallow or pasture):

$$\sum_r R_{3<r<7t} = \sum_r R_{3<r<7t-1} + SA_t - SPe_t \quad (10)$$

Land in forest (considering both mature forest and secondary forest fallow) for a given year starts from a base of land in forest the previous year, less the area cleared

(*CF*), plus land that has been in rehabilitated pasture for five years (after which it has accumulated the biomass equivalent to a three-year fallow, as is explained further below) (*SR*). The pool of land agronomically available for forest (specifically, a new fallow) also includes land that could have been used for perennials (either because it was previously planted to perennials or an annual crop) but wasn't (*SPe*). As before, the farmer may find it economical to defer fallowing some of this land (*SF*), instead allocating it to the alternative suitable use (pasture):

$$F_t = F_{t-1} - CF_t + SR_t + SPe_t - SF_t \quad (11)$$

Pasture in a given year follows the same basic pattern: land agronomically available for this use consists of the previous year's pasture, plus the area that could have been used for fallow, but wasn't (*SF*), minus the area that the farmer decides not to allocate to pasture (*SP*):

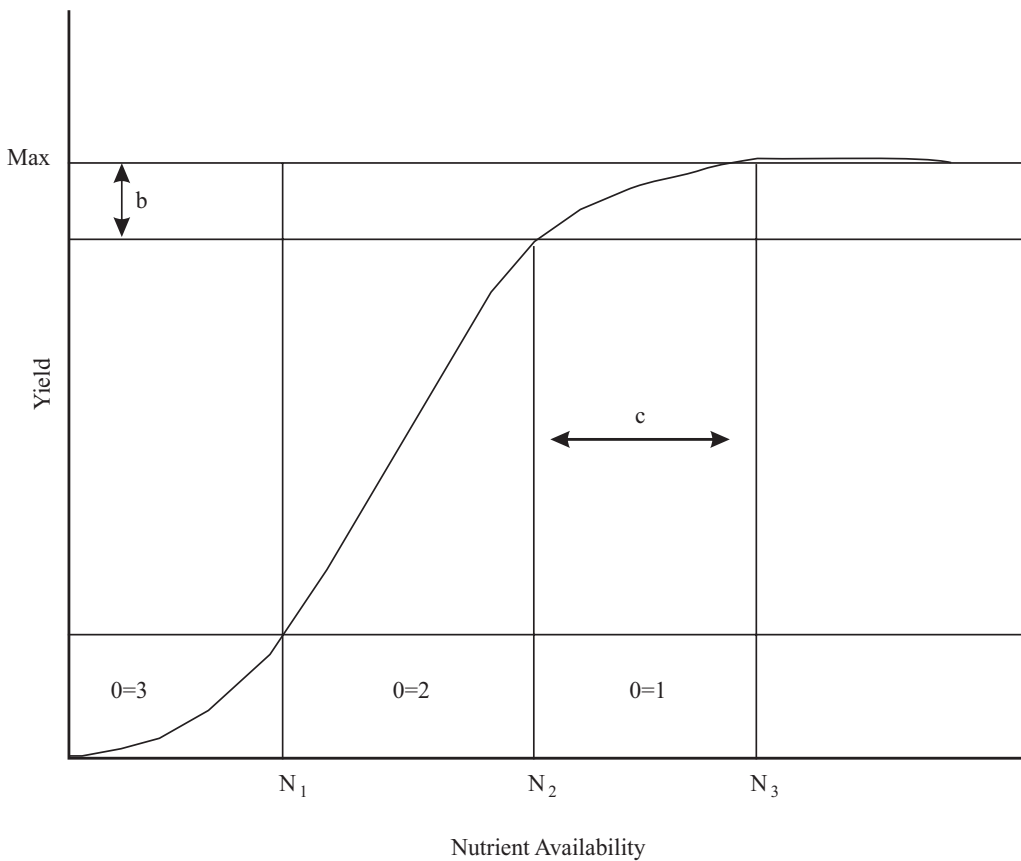
$$\sum_r R_{r>6t} = \sum_r R_{r>6t-1} + SF_t - SP_t \quad (12)$$

This land (*SP*) is switched to a rehabilitating pasture cycle, part of a pool of rehabilitating pasture lasting five years. Land emerging from this rehabilitation cycle (*SR*) enters the forest/fallow category of land as a year=3 fallow, so appears in equation (11), in effect closing the land use "circuit."

As equation (12) indicates, degraded pasture can be replanted or rehabilitated. Rehabilitating pastures are accounted for separately from fallow land (previously dedicated to annual or perennial crops only) to reflect the longer-term nature of investments needed to return them to productive use. Once pastureland has been rehabilitating

⁸⁸Note that, for each variable, the model tracks land in each category suggested by subscripts listed in Table B.2. Equations (9) through (12) present aggregations from the level of detail available in the model up to aggregate land use categories: annuals, perennials, forest, and pasture (that is, across all specific rotations, technologies, and vintages). The subscripts over which the aggregations occur are dropped in equations (9) through (12) for simplicity.

Figure B.1 A hypothetical nutrient response function



for 3 to 7 years, depending on the soil quality, it can return to the normal stock of fallow land and be put back into production. This short-term irreversibility (pasture cannot go directly into other uses) could be eliminated by mechanical tilling and fertilizer applications. However, mechanical tilling is still not economical in the study area, and is not an option in the model.

Stocks of soil nutrients, especially nitrogen and phosphorous, are known to be limited in the study area's soils. Fertilizers can be added to correct for these natural deficiencies, but those available commercially were expensive (in 1994), so most farmers choose not to use them and knowingly ac-

cept lower yields. To account for natural stocks of nutrients and the effects insufficient supplies of nutrients on crop yields, several constraints and relationships were introduced into the model.

Crop nutrient requirements can be met through natural nutrient stocks (*NO*) or by applying fertilizers (the latter source is only valid for V3 technologies and appears in the profit and cost function only).

$$\begin{aligned}
 NO_t + \sum_{r \neq 3} \sum_{v \neq 0} ND_{rv} & \\
 \geq \sum_y \sum_r \sum_v ndr_v R_{r < 7 \text{yrs}} & \quad (13)
 \end{aligned}$$

If available nutrient stocks (regardless of source) are less than those required to

achieve maximum yields, the nutrient deficiency variable (ND) become positive and yields decline:

$$P_{pr<7mt} = \sum_r \sum_y \sum_v yld_{rpr<7yv} R_{ryvt} - \sum_r \sum_{v \neq 3} \sum_o nr_{rprvo} ND_{rvot} \quad (14)$$

From equations (13) and (14) it can be seen that when ND is equal zero, maximum production (P_{pr}) is achieved. However, if nutrient requirements are greater than the stock of nutrients available (that is, when ND is positive), output declines according to the nutrient response function nr (a positive number that linearly maps nutrient deficiencies into yield reductions).

Figure B.1 depicts this relationship, plotting nutrient availability (horizontal axis) against yield (vertical axis). At any point on the horizontal axis to the right of N_3 yields are unaffected by nutrient availability; that is, maximum yields are achieved. As nutrient deficiencies occur (that is, as we move to the *left* of N_3 on the horizontal axis) yields begin to decline, slowly at first, if nutrient levels are between N_3 and N_2 . At N_2 (a decline in nutrient availability equal to c), for example, yield losses are b . The nutrient response function (the curved line in Figure B.1) is thus given by b/c , and output (P) is equal to $[yld_{r=con} - (b/c * ND)] * R_{r=con}$.

That is, total output for a given product is equal to potential yield *minus* yield declines due to nutrient deficiencies times

total area dedicated to that product. The model approximates each rotation's (R) yield response function by linearizing the relationship between nutrient shortfalls and yield, and represents them as three sections of increasing severity of nutrient deficiency shortfall and yield decline:

$o = 1, o = 2,$ and $o = 3$ (the "steps" identified at the bottom of Figure B.1).

If yield declines caused by a nutrient deficiency are "less costly" to a farmer than correcting for them by deforesting new land or applying chemical fertilizers, the model optimally allocates the "stock" of nutrient deficiencies across the various rotations.

If, instead, the model determines that it is less expensive to open new areas (that is, to increase NO , the natural source of nutrients in the model), then fallow or primary forest or both are cleared. To account for these alternative sources of nutrients, the model must keep track of the stock of nutrients in the cultivated areas (equation 15) and stocks in the fallow and forested areas on the farm (equation 16).

$$NO_{t+1} = NO_0 + NO_t + \sum_y \sum_v nf_y CF_{yvt} \quad (15)$$

$$NOF_{t+1} = NOF_0 + NOF_t - \sum_y \sum_v nf_y CF_{yvt} + \sum_{y<7} naf_y F_{yt} \quad (16)$$

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