Land Use Policy 108 (2021) 105660

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Sustainability of agricultural production following deforestation in the tropics: Evidence on the value of newly-deforested, long-deforested and forested land in the Brazilian Amazon

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ARTICLE INFO

JEL Classification:
Q23
Q24
Q56
Q57

Keywords:
Tropical deforestation
Sustainability
Hedonic valuation
Brazilian Amazon

ABSTRACT

Tropical deforestation has typically been characterized as a process with persistent environmental costs (in the form of biodiversity and ecosystem services loss) and short-lived economic benefits (in the form of one-off timber harvests and agricultural fertility boosts). However, this characterization is largely based on agronomic study of tropical soils, and does not fully capture the long-term agricultural potential of cleared land. Landowners can make investments to improve fertility and raise productivity, extending the time horizons over which agriculture is profitable. Whether they choose to make these investments depends on available technologies, the relative prices of inputs and outputs, and the cost of the alternative strategy of clearing additional forest. There is little evidence on how agricultural productivity in the tropics changes over time for individual farmers, because regional development processes confound changes in land productivity when aggregate data are used. Understanding the trajectory of returns to land after tropical deforestation matters because the effectiveness of policies to limit deforestation, promote reforestation, and encourage agricultural intensification all depend on the values of forested and deforested land to farmers and the time horizons over which those values are maintained. This paper estimates the contributions of forested, newly-deforested, and long-deforested land to total property values reported by smallholders in established agrarian settlements in the western Brazilian Amazon. We find—during a decade in which the Brazilian government significantly strengthened its enforcement of forest laws—that deforested land retained its value, the value of forested land *increased* relative to cleared land, and the value of newly cleared land declined.

1. Introduction

In recent decades, the expansion of agricultural land to meet the food demands of a growing global population has largely occurred through clearing intact or disturbed forests in tropical regions (Gibbs et al., 2010; Foley et al., 2011; Pendrill et al., 2019). This expansion is expected to continue, with the growth of agricultural land between 2000 and 2030 estimated at 125–416 million ha worldwide (Lambin and Meyfroidt, 2011). The conversion of tropical forests contributes to rates of carbon emissions and biodiversity loss that are estimated to exceed the planetary boundaries within which humanity can safely pursue social and economic development (Rockström et al., 2009). This process has typically been characterized as inherently unsustainable in the sense that nutrients are extracted from the forest system through logging, cropping and ranching in the short term (Schneider, 1995), but any benefits are short-lived as soil fertility and farm profitability quickly decline (Goodland and Irwin, 1975; Myers, 1991; Rodrigues et al., 2009).

Managing the competing priorities of food production and tropical forest conservation requires knowledge of their net benefits, including how returns to agriculture evolve over time on deforested land. The conventional wisdom on the productivity dynamics of tropical farmland has been based largely on evidence on the physical characteristics of the soils, i.e. that organic matter (Goodland and Irwin, 1975; Townsend et al., 2010), nitrogen and phosphorus (Davidson and Martinelli, 2009; Numata et al., 2007) and carbon storage (Maia et al., 2010) all rapidly decline with deforestation. However, agricultural productivity depends

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https://doi.org/10.1016/j.landusepol.2021.105660
Received 11 May 2020; Received in revised form 21 September 2020; Accepted 20 July 2021
Available online 2 August 2021

not only on soil characteristics, but also on landowner decisions about factors such as fertilizer use, pasture management and crop selection (Barbier, 1997). These decisions in turn depend on availability, cost, and effectiveness of appropriate technologies; relative scarcity of land for ongoing deforestation; and other input and output prices, as determined by the economic and policy context in which landowners operate (Gebremedhin and Swinton, 2003; Mercer, 2004; Kassie et al., 2015). Given the potential role for farmer action in determining soil fertility, the trajectory of agricultural returns on tropical forest frontiers requires data on farmers and their farms. In particular, panel data can reveal how farmer investments to offset or minimize land degradation respond to changes in input and output prices, available technologies, and policies that subsidize input use; disseminate improved methods; or raise the cost of deforesting new land.

This study examines whether the gains from agricultural expansion into tropical forest are inherently temporary–as widely claimed–or whether the long-term returns from agriculture can be stable or even increasing over time. Evidence of non-declining long-term returns would support strategies of stabilizing and intensifying land use through a combination of increased enforcement of forest protection policies, improvements in technology, and "zero deforestation" supply chain interventions. We use stated property values and other property and household characteristics from a spatially-referenced panel survey of farmers in the Brazilian Amazon conducted in 2009, 2005 and 2000. The sample was drawn from agrarian settlements established by INCRA, the national land reform agency, between the 1970s and the 2000s, so properties contain land cleared recently and as much as four decades ago. By Amazonian standards, farmers in our study region of six municipalities in the state of Rondônia have relatively secure property rights, which means that their stated land values should primarily reflect expected future productivity rather than risk of invasion or expropriation. Soils in the region have been rated as relatively well suited for agricultural production by the Brazilian government, allowing us to assess whether settlement in locations that appear promising based on their soil types translates to sustained productivity in practice.

We use a hedonic model to estimate the contributions of newly-deforested ("new") and long-deforested ("old") land to total stated property value. Forest land in Brazilian agrarian settlements is typically cleared incrementally over time (Pacheco, 2009). This makes it difficult to distinguish changes in property values (or profit or income) that result from declines in average land productivity as a settlement ages from changes due to contemporaneous trends such as improvements in technology and infrastructure; changes in enforcement of forest protection policies; the effect of deforestation itself on the value of the property; and any temporal trends in land values due to speculation (Flexor and Leite, 2017). By disaggregating properties into different 'vintages', or areas cleared different numbers of years ago, we are able to estimate how the contribution of a hectare of cleared land to the total value of a property varies with its vintage and distinguish the effect of land vintage from other changes that affect all properties within a settlement simultaneously. We also consider how the relationship between land vintage and land value has changed over time, and place these changes in the context of changes in economic and policy conditions over our 9-year study period.

Our results have important implications for three key areas of policy in Brazil. First, opportunity cost estimates for REDD+ and other conservation policies typically either convert annual returns to land in agriculture into a capitalized value representing the discounted stream of future profits (e.g. Ickowitz et al., 2017; Ma and Swinton, 2011; Naidoo and Iwamura, 2007; Börner et al., 2010), or simulate returns to land in a sequence of uses (Bowman et al., 2012; Börner and Wunder, 2008; Lu and Liu, 2013). Our analysis provides a check on the assumption that annual returns are either constant or decline at an exogenously determined rate, embedded in these opportunity cost estimates. Second, it is necessary to understand relative benefits and costs, including how these values evolve over time, to coordinate and allocate funding across forest conservation and restoration efforts in the context of climate change mitigation and biodiversity conservation. Mature forest is widely recognized as offering unique ecosystem and biodiversity benefits, but there is also a growing literature on the ecological importance of secondary forest (Cole et al., 2014; Junqueira et al., 2010). As a signatory to the global Bonn Challenge for forest restoration, Brazil has pledged to restore 12 million hectares of forest through the National Plan for the Recovery of Native Vegetation (Planaveg) and the restoration requirements of the Forest Code. We contribute to understanding of the relative opportunity costs of forest protection and restoration in the old frontier of the Brazilian Amazon, which is often noted as potential site for restoration efforts. Third, partly in response to criticisms of the lack of sustainability of INCRA settlements (Barbier, 2004; Fearnside, 1997; Smith, 1981), programs that promote the adoption of new technology and provide subsidized credit have been expanded with the objectives of supporting intensification of production and stabilization of the deforestation frontier in the Amazon (Assunção et al., 2020; Newton et al., 2013). We assess whether changes in the expected returns to long-deforested land are consistent with the theory of change of these programs.

2. Conceptual framework

In the immediate aftermath of conversion of tropical forest to cropland or pasture, soil organic matter and resulting fertility are relatively high, due to the release of nutrients when forest biomass is burned. This effect is short-lived as natural levels of inorganic nutrients tend to be low (Sanchez et al., 1982; Numata et al., 2007; Stromgaard, 1984; Tiessen et al., 1994). Due to these physical soil characteristics, it has long been argued that agriculture in tropical forest regions is not sustainable (Goodland and Irwin, 1975; Myers, 1991;Rodrigues et al., 2009), and shifting frontier models have been developed to describe a stylized pattern of short-term cultivation followed by migration of farmers to clear new land as nutrients are depleted following deforestation (Rudel et al., 2002; Perz and Skole, 2003; Sloan, 2007). It is frequently assumed that degraded, unused lands are a relevant target for encouraging reforestation (Brancalion et al., 2016; Celentano et al., 2017; Aguiar et al., 2016). However, some argue that there is potential to increase agricultural output without further deforestation by supporting investments in productivity improvements (Galford et al., 2013; Stabile et al., 2020).

The problem with drawing conclusions about the sustainability of tropical agriculture based on the physical characteristics of the soils is that agricultural sustainability is in large part an economic question of whether households choose to invest in land improvements, rather than simply a technical problem of soil science or plant breeding (Barbier, 1997). As soil fertility declines after deforestation, farmers can take actions to offset processes of nutrient depletion. This is increasingly the case on the Amazon frontier, as research and development in Brazil and elsewhere has expanded knowledge of methods for raising the productivity of degraded cattle pastures. For example, farmers can add inputs such as lime, charcoal or commercially manufactured fertilizers (Sanchez et al., 1982; Lehmann et al., 2003); adopt alternative production systems like agroforestry or silvopastoralism (Fernandes and de Souza Matos, 1995; Montagnini et al., 2013); rotate crops and grazing areas (Carvalho et al., 2017); or plant higher-yielding cultivars (Martha et al., 2012). Whether farmers choose to take these actions depends on their cost in terms of purchased inputs, labor, and/or land use, and their expectations of future productivity.

We follow Barbier (2000) to model the choices available to farmers who face deteriorating land productivity over time. Farmers maximize the profits from discounted future production, which is a function of inputs, including labor, used for production (z_1) and soil quality (x). Farmers can choose whether to invest in soil improvements; deforest new land; do both; or do neither. Soil quality is an increasing function of inputs used for soil conservation (z_2) and the area of newly deforested land (D) and a decreasing function of inputs used for production. A constant (k_0) reflects fixed aspects of soil quality. We assume complete labor, other input and output markets, so farmers face exogenous input (c) and output (p) prices. Total cumulative deforestation cannot exceed the size of the property ($\overline{D}$).

$$max \quad V_1 = \lim_{T\to\infty}\int_0^T e^{-rt}[pf(x, \quad z_1) - c_1 z_1 - c_2 z_2 - c_d D]dt$$

$$s.t. \quad \frac{dx}{dt} = \dot{x} = k_0 + h(z_1, z_2, D), \quad h_1 \le 0, h_2 \ge 0, \quad x(0) = x_0, \quad k_0 \ge 0$$

$$\sum D_t \le \overline{D}$$

The first order conditions show that, when the deforestation constraint is not binding, farmers will invest in land improvements until the future and current value of higher quality soil from either investment in soil improvements or deforestation are equal to the foregone earnings from current depletion of the soil:

$$\dot{\mu} + pf_2 = r\frac{c_2}{h_2} = r\frac{c_d}{h_d} = -r\frac{pf_1 - c_1}{h_1}$$

where μ is the shadow value of soil quality.

The decision about how much to invest in land improvements therefore depends on the costs of production and conservation inputs, the effectiveness of conservation technologies for improving soil quality, and the role of soil quality in the agricultural production function. In practice, farmer perceptions of these factors may also depend on their knowledge of inputs or production systems through observation of neighbors or interaction with extension agents; their access to credit for investment in improved technologies; and their time horizons for decision-making, as influenced by land tenure security (Gebremedhin and Swinton, 2003; Mercer, 2004; Kassie et al., 2015; Latawiec et al., 2014; Teklewold et al., 2013; Maertens and Barrett, 2013).

The other key determinants of farmer choices are the costs and benefits of clearing new land. The costs of deforestation include the value of any foregone ecosystem services from standing forests, and any sanctions from illegal deforestation or liabilities for reforestation to comply with the Forest Code. If these costs are low, it will be rational for farmers to extract short-term rents by farming high-nutrient soils immediately after deforestation, and then convert more forest rather than investing in improving cleared land as those nutrients are depleted (Barbier, 1997; Schneider, 1995). If the cost of newly cleared land increases, for example due to the risk of penalties for illegally clearing forest, the returns to investing in land improvements will increase relative to the returns to clearing new land. On the other hand, development of improved technologies or agricultural policies to encourage soil investments will raise the expected long-term productivity, and therefore the value, of newly cleared land, and as a result incentivize additional forest clearing.

The value of agricultural land is typically assumed to be equal to the net present value of expected annual profits from that land (Goodwin et al., 2003). Investments in land improvements increase the value of that land by reducing the rate at which productivity declines. The value of forest land is equal to the net present value of expected benefits from uncleared land in the highest valued future use of that land. It therefore captures the value of the option to clear the land for agriculture in a future time period plus the value of standing forest during the time until the land is cleared. The value of the option to clear the land reflects the value of potential land improvements and the time period over which cleared land is expected to be productive. The value of standing forest includes amenity values from forests or production activities such as non-timber forest product collection, as well as local ecosystem services such as soil and water protection. Importantly in our context, it also includes the value of avoiding sanctions for illegal deforestation or relief from legal requirements to reforest cleared land.

We estimate how farmers' perceived value of cleared land varies with the length of time since it was first cleared and how their values of forested land and cleared land of different vintages have evolved over time. The physical and agronomic evidence on the high nutrient content of newly-cleared land suggests that the value of cleared land is likely to decline with its age. However, the extent and speed of that decline will depend on investments in land improvements made by farmers. We assume that farmers have full information about potential improvements and therefore incorporate that information into the stated values of their properties and their investment decisions. Thus, the value of cleared land of different vintages depends on the factors that shape decisions about these investments, including the costs of conservation inputs, the effectiveness of available technologies, the time horizons over which farmers operate, and the costs of the alternative strategy of clearing new land. Each of these may vary over time, with frontier development and changes in policy environment.

3. Methods

3.1. Description of the study region

3.1.1. Brazilian Amazon

The Brazilian Amazon epitomizes the tension between conservation and development, with the world's greatest stock of forest carbon and unmatched biodiversity (Malhi et al., 2008) at stake on the one hand, and the development of one of the poorest regions of Brazil on the other (FAO, 2010). Brazil administered one of the most extensive frontier colonization programs in the past century, settling over one million individuals in the Amazon since 1970 with oversight by the National Institute of Colonization and Agrarian Reform (INCRA) (Schneider and Peres, 2015). These settlements cover only 8% of the more than 5 million square kilometers within the Legal Amazon, but they are four times more densely populated than rural areas without INCRA settlements (Schneider and Peres, 2015) and account for approximately 21% of total deforestation (Yanai et al., 2015).

The INCRA settlement program has been criticized for similar reasons as agricultural expansion programs in other tropical forest areas, namely that the environmental costs are high and that the land does not support sustainable agriculture over the long term (Goodland and Irwin, 1975; Rodrigues et al., 2009; Murphy et al., 1997; Schneider et al., 2002). This has been argued to lead to a mobile frontier in which farm households abandon degraded land on the old frontier, clearing new land further into the forest (James, 1938; Casetti and Gauthier, 1977; Barbier, 1997; Rudel et al., 2002). However, this cyclical pattern of settlement and associated deforestation may no longer dominate regional land use (Campari, 2005; Caviglia-Harris et al., 2016). First generation settlers are more likely to remain on their original land allocation, and second generation settlers now typically remain in close proximity to the original homestead (Richards, 2015; Caviglia-Harris et al., 2013; VanWey et al., 2012), in many cases moving to small towns and cities nearby (Macdonald and Winklerprins, 2014; Ludewigs et al., 2009).

The Brazilian Amazon has experienced expansion of regional urban markets, global demand for commodities such as soy and beef, and transportation infrastructure, all of which potentially raise returns to agricultural investment on the frontier. Research and policy initiatives have sought to stabilize productivity and maintain pasture stocking rates on deforested land to decouple commodity production from further deforestation (Cohn et al., 2014). In particular, Brazil's Nationally Determined Contribution (NDC) under the Paris Agreement on climate change includes multiple actions that are intended to create incentives for sustainable land management rather than new deforestation. One component of the NDC is the Low Carbon Emission Agriculture (ABC) plan, which provides low-interest credit to support activities such as agroforestry, restoration of degraded pastures, and technologies for improved nitrogen uptake in soils (Gurgel and Costa, 2014). The more recent *Rural Sustentável* program has similar objectives and aims to help overcome barriers to farmer participation in the ABC plan such as insufficient knowledge, technical capacity, credit access, and motivation (Newton et al., 2016). These recent programs built on prior programs to support agricultural intensification such as Pronaf (Programa Nacional de Fortalecimento da Agricultura Familiar, National Program for Strengthening Family Farming), which has provided subsidized credit for small-scale producers since 1996, with expansion in 2004 (Assunção et al., 2020), and the research efforts of EMBRAPA, the agricultural extension agency, to increase the productivity of agriculture (Martha et al., 2012). More broadly, scientific advances in land management practices (Junqueira et al., 2016) and technological developments such as new breeds of cattle and varieties of grass (Carneiro et al., 2014; Mazzetto et al., 2015; Müller et al., 2004; Siqueira and Duru, 2016; Carvalho et al., 2017) weaken the link between soil fertility and agricultural productivity.

The NDC also calls for continued investment in strengthening enforcement of the Forest Code, with the objective of achieving zero illegal deforestation and restoring and reforesting 12 million ha of forests by 2030 (Ministerio do Meio Ambiente, 2016). This increases the *de facto* costs of new deforestation for farmers. Monitoring and enforcement were strengthened in ways that led to overall reductions in deforestation between 2004 and 2012, although increases have been observed in more recent years (INPE, 2019). For example, the 2004 National Plan to Prevent and Control Deforestation in the Brazilian Amazon (PPCDAm) expanded forest conservation regulations and incentives, and employed the world's largest and most advanced real-time deforestation monitoring system (DETER – Detection of Deforestation in Real Time) to support enforcement (Assunção et al., 2014). These efforts have been met with significant political resistance from the agricultural and other pro-development lobbies that have sought to undermine environmental laws (May et al., 2011). For example, controversial revisions to the Forest Code in 2012 provided amnesty for smallholders who deforested land prior to 2008, although at the same time new tools for conservation were introduced such as the Rural Environmental Registry (CAR), which requires individual landowners to identify the areas on their property that must be protected or restored (Soares-Filho et al., 2014; Azevedo et al., 2017; Biggs et al., 2019).

3.1.2. *Ouro Preto do Oeste region*

The Ouro Preto do Oeste (OPO) region (composed of six municipalities) is located in central Rondônia, a state in the southwestern Brazilian Amazon near the border with Bolivia. The state of Rondônia experienced the most extensive and rapid land transformation (from forest to farmland) in the Brazilian Amazon in the 1980s and 1990s (Alves, 2002), making it a priority area for monitoring and managing development pressures. This rapid transformation of the landscape was accompanied by the development of dozens of urban centers, and improvements in transportation, education, and health.

The development of the state was initiated by the construction in the early 1960s of two federally funded highways traversing the Amazon (Paraguassu-Chaves, 2001), as part of an intentional effort by the Brazilian government to spur migration to demonstrate control over and populate the Amazon. Approximately 80% of deforestation in the state through 1996 had occurred within 12.5 km of the major highway, BR-364, which runs from the southwest through the Ouro Preto do Oeste study region to the capital city of Porto Velho in the north of the state (Alves, 2002). In addition to building roads, the federal government established agrarian settlements through the national land reform agency, INCRA (Instituto Nacional de Colonização e Reforma Agrária - National Institute for Colonization and Agrarian Reform). Because our study region is both bisected by a federal highway and comprised nearly entirely by INCRA settlements, it was more than 80% deforested by 2010 (INPE, 2011). In the state as a whole, deforestation increased from approximately 2% in 1977, to 5% by 1990, to 20% in 2000, and to over 36% by 2010 (INPE, 2011).

When agrarian settlements were first established in Ouro Preto do Oeste, colonists grew annual (maize, rice, beans, and manioc) and perennial (cacao, coconut, and coffee) crops in addition to raising cattle (Caviglia, 1999), but markets have transitioned to dairy, beef, and fish. Markets are fairly well integrated and complete for most inputs and outputs, notably including milk with up to 11 dairies operating in the region in our survey years. Establishment of these dairies was accompanied by rapid growth in the region's cattle herd, consistent with a general trend towards ranching in the Amazon (Schneider et al., 2002; Walker et al., 2000; Mertens et al., 2002; Bowman et al., 2012) and in Rondônia (Browder et al., 2004). Land markets exist, but are thin, preventing the use of actual sales values for the hedonic analysis in this paper. The average price of farmland in this region is similar to the rest of the Amazon, although lower than national farmland prices (FNP Consultoria e Comercio, 2013; Walker, 2003). As in other parts of the 'arc of deforestation', prices have been rising substantially over the past 20 years, in particular for land and agriculture and pasture (Fig. 1). For example, the real price of one hectare of cropland increased by almost 700% in Mato Grosso, 400% in Pará and 200% in Rondônia between 2000 and 2010. And although lower in value, the price per hectare of pasture increased by almost 350% and the price per hectare of forest increased by 200% in Rondônia between 2000 and 2010 (Table 1).

3.2. *Empirical model*

We investigate how the value of land evolves after deforestation with a hedonic model of stated property values estimated as a function of the area of cleared land and other characteristics of the property. Hedonic price models are useful tools for unbundling the contributions of diverse attributes to property values (Geoghegan, 2002). For example, when environmental services are valued by property owners (either explicitly or implicitly), the provision of these services is reflected in property prices (Ma and Swinton, 2012). Typically, this type of analysis uses data on real estate transactions, although self-reported property values are also used (Roka and Palmquist, 1997; Goodwin et al., 2003; Boisvert et al., 1997). In forest frontier regions, because there are no databases for property sales and characteristics surveys and stated preference models are often used to estimate the value forest services (Tuffery, 2017; Kim et al., 2016; Klaiber and Smith, 2013). We therefore use

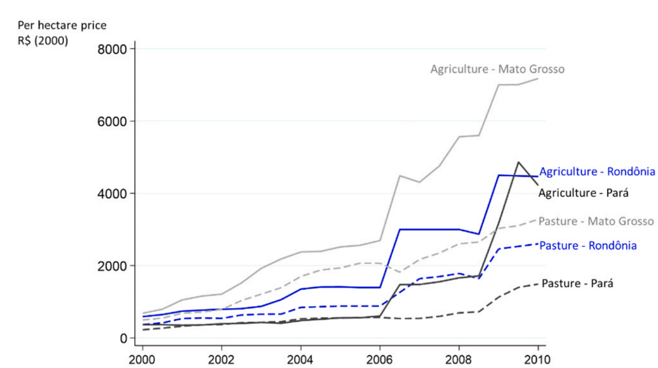

Fig. 1. Illustration of how land vintages are calculated per property: in the reference year (2000 in this case) we only observe forest and the total area of cleared land. Vintage is calculated using past land use images. 'Old' land had already been cleared 15 years prior to the reference year (1985 in this case); 'medium' land had not been cleared 15 years prior, but had been cleared by 5 years prior (1995 in this case); and 'new' land had not been cleared by 5 years prior, but had been cleared by the reference year.

Table 1
Comparison of stated land prices with estimates based on land sales (per hectare nominal Brazilian R$).

	Rondônia (estimates from land sales)			Survey responses (stated values)
	Agriculture	Pasture	Forest	
2000	1683	581	177	1409
2001	2118	844	180	
2002	2231	851	187	
2003	3024	1399	230	
2004	4367	2075	250	
2005	4242	2002	238	2574
2006	4211	1921	231	
2007	4347	2149	230	
2008	4754	2383	354	
2009	4499	2463	405	2689
2010	4466	2603	536	

Notes: Survey data suggest that agriculture decreased in area on the property from 6.5 (13%) to 4.2 (10%) and 3.2 (10%) hectares from 2000 to 2005 and 2009. Pasture increased from 45.3 (68%), 43.6 (72%), and 41.9 (88%) hectares from 2000 to 2005 and 2009. Forest decreased from 11.7 (18%), 6.4 (10%), and 6.4 (11%) hectares from 2000 to 2005 and 2009.
*Source: Informa Economics – IEG FNP (*www.informaecon-fnp.com) Land prices are estimated to serve as investment information for agribusiness companies. This is the most complete source of land prices data available in Brazil.

directly elicited farm (or lot) prices, which reflect both the expected future returns to the land and the value of buildings and other permanent improvements to the lot. Our hedonic model is designed to unbundle these values to gain insight on how the value of cleared land evolves over time.

In the traditional hedonic price framework, the overall property value V_{it} is a function of the values of each of the attributes of the property that contribute to the overall income or utility of the household. For this paper, the specific attributes of interest are how much forested land has been cleared for crops, pasture, or other purposes, and the length of time since that deforestation occurred. We consider only the initial clearing of mature forest, and not any subsequent cycles of regrowth and clearing. We also include geographic and biophysical characteristics of the land and the property, as well as characteristics of the survey respondent's household:

$$V_{it} = v(L_{ait}, X_{bit}, \quad H_{cit})$$

where L_{ait} represents the cleared land on each property *i*, at time *t*, disaggregated since the time since it was first cleared (*a*), X_{bit} is a vector of land quality attributes (*b*), including the presence of water on the property, the soil type, and the distance to market, and H_{cit} is a vector of household characteristics (*c*) including the demographics and human capital of the family. Household characteristics should not affect the market value of land in principle. However, to the extent that stated values reflect willingness to pay by survey respondents, they may be influenced by the needs and preferences of the household. In our estimation of the opportunity cost of preserving forest we are essentially estimating the coefficients on the L_{ait} matrix while controlling for other factors. These coefficients represent the contribution to the total value of the property that can be attributed to one additional hectare of cleared land of a given vintage, holding all else constant.

There are a number of econometric issues to be addressed in the estimation of this model. First, there may be spatial correlation in the unobserved determinants of land values among properties within the same settlement or municipality, or correlation in the values of the same property over time. There may also be endogeneity, in the sense that unobserved heterogeneity in land quality could influence both land use and land values. We therefore relax the assumption of uncorrelated errors and control for unobserved heterogeneity by estimating linear mixed-effects models with time fixed effects; settlement or municipality fixed effects or both; and property random effects. We also include the vectors of land quality and household characteristics described in the previous paragraph as covariates to control for potential influences on both land value and land use decisions, that may be spatially correlated. We test whether spatial autocorrelation in the error terms remains after the inclusion of spatial fixed effects and land characteristics using Moran's I test. Second, the parameters on the land-cover types, i.e. the estimated values of each land type, may vary over time as available technologies and the policy environment change. In fact, we are particularly interested in whether and how they change over time. We therefore allow for the possibility that the parameters in the hedonic panel models are not constant by including interaction effects between year and land type.

Our econometric specification is:

$$V_{it} = \alpha + \sum \beta_{at} L_{aijkt} + \sum \gamma_b X_{bijkt} + \sum \delta_c H_{cijkt} + year_t + \varphi_j + \mu_k + \varepsilon_{it}$$

Where L_a includes hectares of land cleared different numbers of years prior to a reference date as well as hectares of forest land on a given property (*i*), X_b includes property characteristics and H_c includes household characteristics. We include settlement (φ_j) and municipality (μ_k) fixed effects, and the hedonic prices given by the coefficients on L_a vary with $year_t$. All of the properties in our study region were fully forested when first settled and changes in property sizes have been minimal.

3.3. Data

Data used in the analysis are from a panel survey with three waves in 2009, 2005 and 2000. In each of these years, surveys were conducted with farmers in the six municipalities within the greater Ouro Preto do Oeste region. The sample of farmers was originally drawn on a systematic random stratified basis, using colonization agency maps as a sampling frame for each municipality and included a total of 171 randomly selected households.[1] In the subsequent years, a panel was maintained by revisiting each of the original properties. If a family moved, the new family living on that same lot was interviewed. The survey of landowners elicited information on a wide range of characteristics of both the family and the property.

Respondents were asked how much they would expect to pay for an equivalent property to their own, implicitly assuming that the real estate market in the region is in equilibrium. Specifically, we asked survey respondents "What is the value of your property?", and followed up with "If you were going to buy a similar lot for your children, equal in size, infrastructure, and the same quality (including soils) how much would you pay?". We used this wording to avoid endowment effects, the influence of emotional attachment to the lot, and any hopes or worries that there are interested buyers. Stated land values not only capture farmers' knowledge of current physical agricultural yields and resulting financial returns, but also their expectations about how market prices or available technologies are likely to change in future. These expectations are key to their assessment of the prospects for long-term productivity and are also likely to directly influence land use dynamics. To unbundle the stated values, we also elicited information on lot characteristics. Sills and Caviglia-Harris (2009) found that stated values are strongly associated

[1] The sample for the panel dataset was drawn in 1996, but we do not use the first wave because the stated lot values were not elicited at that time. In each municipality, sampling started with a random lot and included every i^{th} lot after this; where i was determined by the number of properties in the municipality and the percentage goal: "i" was set equal to the number to be interviewed in the municipality (4% of the properties) divided by the number of rural properties in that municipality. This systematic sampling approach reduces the likelihood of spillovers, since immediate neighbors are not included in the sample. For more detail on the survey instrument and methods, see Caviglia-Harris et al. (2012).

Table 2
Descriptive statistics[a].

	2000 Mean (sd)	2005 Mean (sd)	2009 Mean (sd)
Stated value of property (2000 R$)	72,367.35	139,433.04	129,424.42
	(55,362.82)	(119,844.03)	(99,040.73)
Property size (ha)	77.10	67.17	66.39
	(32.65)	(36.31)	(36.42)
Cleared land area (ha)	62.11	56.65	58.76
	(29.02)	(32.22)	(32.99)
Area of land cleared >15 years ago (ha)	27.04	32.17	39.00
	(21.33)	(24.78)	(29.71)
Area of land cleared 5–15 years ago (ha)	25.42	20.86	16.10
	(15.04)	(15.01)	(13.55)
Area of land cleared <5 years ago (ha)	9.67	4.89	3.87
	(8.66)	(7.22)	(6.50)
Mature forest area (ha)	14.63	8.98	7.11
	(12.50)	(10.63)	(9.36)
Soil quality = 1 (good); proportion	0.204	0.165	0.164
Soil quality = 2 (moderate); proportion	0.381	0.353	0.340
Soil quality = 3/4 (poor/very poor); proportion	0.415	0.481	0.500
Mean slope (degrees)	5.04	5.13	5.22
	(2.82)	(3.02)	(3.08)
Travel time to city (minutes)	67.31	61.22	61.73
	(31.81)	(27.46)	(27.05)
Travel time to nearest urban center (minutes)	21.73	21.85	21.82
	(10.11)	(11.80)	(11.96)
Percent forest land within 5 km	21.48	18.71	15.53
	(11.58)	(9.73)	(8.64)
Water source on property (binary)	0.27	0.79	0.98
	(0.45)	(0.41)	(0.16)
Garden on property (binary)	0.68	0.64	0.58
	(0.47)	(0.48)	(0.49)
Electricity on property (binary)	0.65	0.86	0.97
	(0.48)	(0.35)	(0.17)
Family size	7.58	5.65	5.23
	(5.79)	(3.62)	(3.10)
Average age of HH heads (years)	48.21	49.52	52.32
	(12.21)	(13.76)	(14.20)
Average education of HH heads (years)	2.52	3.05	3.35
	(1.61)	(2.21)	(2.76)
Origin of family (1 = South or Southeast)	0.84	0.76	0.77
	(0.37)	(0.43)	(0.42)
Observations	147	266	244

[a] Prices are adjusted for inflation using the World Bank Consumer Price Index. R$2 was approximately equal to US$1 in 2000.

with the size and location of the property, while investments such as home gardens and neighboring land uses also play a role. We include these characteristics in our model.

The average reported lot value was around R$73,000 in 2000, R $148,000 in 2005 and R$138,000 in 2009 (Table 2) in constant 2000 prices,[2] which corresponds to about R$950 to R$2000 per hectare. Stated property values are higher in the municipalities of Ouro Preto do Oeste (the municipality with the city center), Teixeirópolis and Vale do Pariso, and lower in Mirante da Serra and Urupá, the most recently settled municipalities located further from the city center, in each of the survey years. In response to a follow-up question, nearly half (44%) of the respondents reported that the primary factor determining their stated value was recent sale prices of other properties within the region,

[2] Prices are adjusted for inflation using the World Bank Consumer Price Index. R$2 was approximately equal to US$1 in 2000.

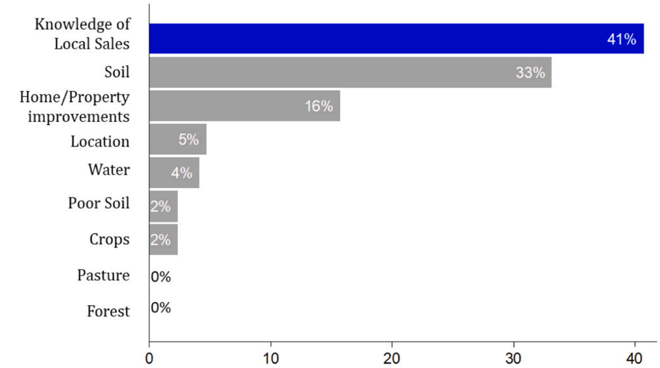

Fig. 2. Real property prices are on the rise in the states in the arc of deforestation.
Source: Informa Economics – FNP (www.informaecon-fnp.com).

suggesting that they were reporting their best approximation of the market value of their property (Fig. 2). Variation in stated values is significantly explained by the present value of annual farm revenues and the areas of cleared and forested land (R^2 =0.29), and the predictive power of the model increases when these variables are combined with covariates that reflect the value of the property as a residence in addition to its value for agricultural production ($R^2 = 0.36$).[3]

Stated property values are roughly comparable to secondary statistics on the price per hectare of various types of land. INCRA reports the value of ‘unimproved’ land by municipality. As would be expected for ‘improved’ properties, the average value per hectare reported by farmers in our sample is much higher (1.7–2.3 times), but the variation across municipalities is consistent, with a correlation coefficient of 95% (INCRA, 2004). A private consulting and agribusiness information firm in Brazil also reports regional market values for agriculture, pasture and forest land (FNP, 2013). On a per hectare basis, the stated property values in each wave of the survey fall within the range of values reported by FNP for land used in agriculture, pasture and forest (Table 1).

The main independent variable of interest is the area of cleared land, as we want to estimate how an additional hectare of deforestation affects the value of the property into the future. This is based on remote sensing of land cover within the boundaries of the property. The land cover classifications are generated using a decision tree classifier with spectral mixture analysis, applied to standardized remotely sensed variables from Landsat 5 and Landsat 7 images between 1984 and 2009 (Numata et al., 2009; Roberts et al., 2002). Cleared land in each survey year (2000, 2005, and 2009) is calculated as the difference between the total area of the lot, based on INCRA cadastral maps, and the area of mature forest. It therefore includes pasture, cropland, secondary forest and land used for buildings or domestic gardens. It does not include areas that cannot be used by the household for production or residence such as bare rock or water. We assume that cleared land is in the highest-value use at any point in time, and we aim to estimate the value of that use regardless of what it is and allowing for the possibility that it changes over time.

In addition to the aggregate measure of cleared land in each survey year, we calculate areas of three separate vintages of cleared land, based on the time since they were deforested. ‘Old’ cleared land was deforested at least 15 years before the survey year; ‘medium’ cleared land was cleared between 5 and 15 years before the survey year; and ‘new’ cleared land was cleared within 5 years of the survey year. As illustrated in Fig. 3, for the 2000 survey year, the area of ‘old’ cleared land is the difference between the total area of the lot and the area of mature forest

[3] Full estimation results available from corresponding author on request.

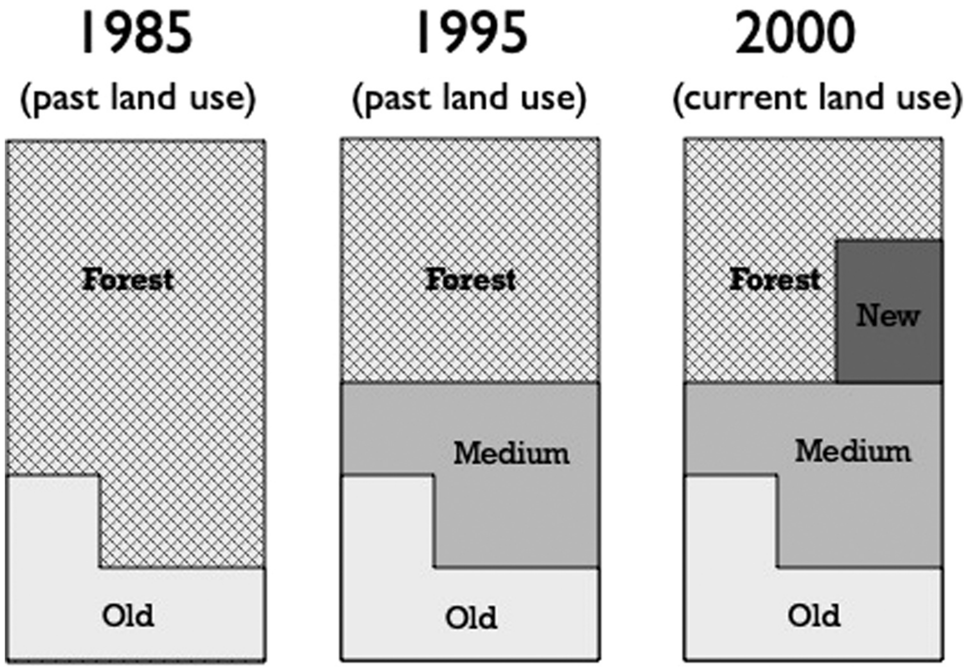

Fig. 3. Forty one percent respondents state that knowledge of the sale prices of nearby properties most influenced the reported property value (year = 2000; n = 172).

in 1985; the area of 'medium' cleared land is the difference between the area of the lot and the area of mature forest in 1995, minus the area of 'old' cleared land; and the area of 'new' cleared land is the difference between lot area and mature forest area in 2000, minus 'old' and 'medium' cleared land.

Table 2 shows the total areas of cleared and forested land, and the areas of cleared land of each vintage, in the survey years 2000, 2005 and 2009. The mean total area of sample properties fell slightly from 77 ha to around 70 ha between 2000 and 2005, and then remained approximately constant. The majority of land had been cleared of mature forest, leaving an average of 14.5 ha of forest in 2000, declining to 7.5 ha by 2009. By 2000, over 40% of cleared land had already been cleared at least 15 years prior, and this proportion of land that was 'old' increased to around two thirds by 2009. Consistent with these trends in 'old' land, only a small proportion of cleared land in any given year has been deforested within the prior five years. In 2000, 16% of land was 'new', falling to 6–7% in the later time periods.

Other control variables are also listed in Table 2. The soils of most properties are rated as having moderate to poor ability to support agriculture, and properties are in general reasonably flat, with an average slope of just over 5 degrees. The travel time to the main urban center of Ouro Preto do Oeste does vary somewhat over time due to road improvements, with the average property being about one hour drive away. The final lot characteristic we include is the proportion of the land surrounding the lot that is in forest. This is potentially important because forest generates externalities (e.g. by influencing the microclimate, soil erosion and water quality), so the value of a given property may not be solely determined by the land use on that property. We obtain this measure using the same remote sensing data described above to calculate the percent of land that lies within a 5 km buffer around the property that is in mature forest.

In the final specification of the model, we also include household characteristics. Average household head age increased over time from 48 to 52 years old, which is less than the changes that would occur solely due to the passage of time. This, along with the change in education (from an average of 2.5–3.4 years), is due to some turnover of household heads within a family for younger and more educated individuals. Approximately 80% of the sample reported that their family originally migrated from the south or southeast of Brazil. This is included in the model because these are relatively wealthy regions of the country so migrants tend to have higher initial levels of human and physical capital than migrants from other regions.

4. Results

We estimate stated property value as a function of the areas of different vintages of cleared land, area of forest land, and other physical characteristics of the property. The coefficients on cleared land in Tables 3–6 can be interpreted as the contribution of an average hectare of cleared land to the total stated value of the lot. We present results from OLS and 2-level and 3-level mixed effects specifications, where the 2-level model includes municipality fixed effects and property random effects, and the 3-level model includes municipality and settlement fixed effects and property random effects. All models include year fixed effects, and the models in Tables 4–6 include interactions between year and areas of each land type or vintage. To simplify the interpretation of results, rather than the regression coefficients, Tables 4–6 show average marginal effects of an additional hectare of cleared land by year, accounting for the year interaction terms. Our initial results (Tables 3 and 4) show the contributions of an average hectare of all cleared land and forest land. Subsequent analyses (shown in Table 5) disaggregate cleared land area by vintage, i.e. the length of time since it was first cleared.

The results in the first three columns of Table 3 show that the value of cleared land varies by year. The area of cleared land is not related to the overall value of the property in 2000 but in 2005, property values are R$1562 higher per hectare of cleared land, and in 2009, property values are R$1262 higher per hectare of cleared land. The contribution of a hectare of forest land to the overall value of the property increases over the three time periods, from zero to R$2356/ha in 2009. We find that the physical characteristics of the property such as slope, soil quality and surrounding land use are generally not significant determinants of value, which may be because of limited variation in the sample. However, proximity to Ouro Preto do Oeste, the main urban center, raises the stated value of the property, which is consistent with the von Thünen model of land rents. In 2000, soil quality affects stated property value, as

Table 3
Stated value of lot as a function of land use and lot characteristics.

	(1) OLS – 2000	(2) OLS – 2005	(3) OLS – 2009	(4) Pooled OLS	(5) 2-level Mixed effects	(6) 3-level Mixed effects
Cleared land area (ha)	260.9	1550.6***	1248.7***	1182.5***	1063.2***	1182.3***
	(223.0)	(237.1)	(228.1)	(154.8)	(236.6)	(149.1)
Mature forest area (ha)	-230.0	1098.3*	2364.0***	728.2**	482.3	673.4**
	(342.6)	(650.9)	(504.6)	(332.8)	(388.4)	(333.9)
Soil quality= 2 (base:1 = good)	-4695.3	-24234.5	-3851.5	-11143.1	-10103.5	-11402.4
	(16,589.6)	(21,890.1)	(17,791.6)	(12,255.5)	(12,531.7)	(12,405.6)
Soil quality= 3 or 4 (base:1 = good)	-28054.5*	-21151.1	-9773.9	-13321.9	-15543.4	-13694.5
	(15,172.7)	(18,007.8)	(14,736.9)	(10,519.9)	(11,649.5)	(11,628.4)
Mean slope (degrees)	-198.7	1980.5	-1073.6	132.5	271.0	144.8
	(1586.8)	(1906.1)	(1251.5)	(1052.7)	(1337.6)	(1350.2)
Travel time to city (minutes)	-526.1**	-1100.8**	-947.1**	-937.2***	-965.2***	-952.9***
	(255.2)	(546.8)	(375.1)	(258.1)	(228.3)	(217.2)
Travel time to nearest urban center (minutes)	272.7	-2.530	629.6	331.9	419.2	346.8
	(522.4)	(835.5)	(605.8)	(428.2)	(426.5)	(388.6)
Percent forest land within 5 km	-282.3	962.7	215.2	227.9	331.3	222.8
	(679.3)	(824.9)	(788.7)	(459.3)	(575.6)	(544.0)
Water source on property	-2791.8	21,685.1	33,261.8	41,374.0***	42,003.0***	42,335.8***
	(9653.2)	(16,357.3)	(43,331.0)	(7914.7)	(7986.3)	(7894.1)
Garden on property	20,428.5**	19,449.3	6187.5	11,492.9*	12,286.4*	11,518.7*
	(7847.3)	(12,871.1)	(10,376.8)	(6781.7)	(6673.6)	(6720.5)
Electricity on property	-4527.5	28,014.0**	47,777.9**	23,273.2***	23,386.8**	22,269.8**
	(8213.0)	(11538.3)	(22117.9)	(7247.3)	(9956.1)	(9969.2)
Constant	106,051.5***	59,591.7*	15,539.5	51,988.1**	17,383.6	53,307.5**
	(33,434.9)	(34,587.0)	(61,107.4)	(23,045.8)	(29,177.1)	(24,790.4)
Observations	145	258	240	643	644	643
Adjusted R^2	0.352	0.442	0.377	0.371		
Moran's I (χ2, with P-value in parentheses)	0.44	2.17	1.48			
	(0.4445)	(0.1403)	(0.2242)			

Notes: All mixed effects models include municipality and time fixed effects and property random effects; 3-level mixed effects models also include settlement fixed effects.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

Table 4
Marginal value of an additional hectare of cleared land, disaggregated by year of data collection.

	(1) Pooled OLS-Year	(2) 2-level Mixed Effects-Year	(3) 3-level Mixed Effects-Year
Cleared land area (ha)			
Year = 2000	176.3	-3.955	99.83
	(190.8)	(304.6)	(263.7)
Year = 2005	1695.0***	1588.1***	1677.8***
	(203.5)	(259.3)	(178.7)
Year= 2009	1109.4***	1002.8***	1092.4***
	(194.2)	(258.6)	(178.5)
Mature forest area (ha)			
Year = 2000	-109.3	-230.9	-60.88
	(296.0)	(544.7)	(518.9)
Year = 2005	1184.4*	1043.5**	1223.0***
	(642.9)	(494.6)	(459.1)
Year = 2009	2293.9***	1951.8***	2166.1***
	(487.3)	(574.2)	(541.0)
Observations	643	644	643
Adjusted R^2	0.455		

Note: Standard errors in parentheses
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

does the presence of a garden on the property. In 2005 and 2009 electricity access appears to raise property values; for example, having access to the grid in 2009 is associated with property values that are R $48,000 higher on average than those without access. Moran's I tests show no evidence of spatial autocorrelation in the error terms in any of the annual models.

Columns 4–6 of Table 3 show the results of panel models estimated with data from all time periods. Cleared land values are consistently around R$1000/ha across these models. Forest land values are lower, at around $700/ha in the pooled OLS and 3-level mixed effects model, and insignificant in the 2-level mixed effects model. However, the single-year models suggest that information is lost by pooling all years. The panel models suggest that the presence of a water source on a property raises its stated value by over $40,000 on average, electricity raises average values by around R$20,000, a garden raises average values by around R$10,000, and being 20 km closer to the city raises values by around R$19,000. In Table 4 we re-estimate the panel models with land values disaggregated by the year the data was collected. These results are consistent with the single-year models in that neither areas of cleared land nor area of forest land are significant in 2000, cleared land is most valuable in 2005, and forest land is most valuable in 2009.

The preceding results may be influenced by changes in the composition of different vintages of land or changes in market conditions (e.g. labor markets), policies, or production technologies over time. The models estimated so far assume that all cleared land has the same value, regardless of when it was cleared. Land in this region began to be cleared in the late-1970s, so the decline in land values between 2005 and 2009 may indicate that the productive lifespan of the land is being reached. However, the theoretical model in Section 2 shows that land values are also influenced by changes in available technologies and the policy context. A single measure of cleared land, encompassing some that has been cleared recently and some that has been cleared many years prior, confounds the effects of changes in average land vintage with changes in technology or policy.

To separate these influences, Table 5 shows pooled OLS and mixed effects results with cleared land disaggregated by vintage using property random effects; year, settlement and/or municipality fixed effects and

Table 5
Marginal value of additional hectare of cleared land: disaggregated by vintage of land and year of data collection.

	(1) Pooled OLS-Year	(2) 2-level Mixed Effects-Year	(3) 3-level Mixed Effects-Year
Area of land cleared >15 years ago (ha)			
Year = 2000	362.4	333.6	339.7
	(348.4)	(420.5)	(383.8)
Year = 2005	2120.6***	2179.8***	2108.6***
	(305.2)	(338.1)	(253.2)
Year = 2009	1301.4***	1365.5***	1268.2***
	(218.8)	(308.4)	(214.5)
Area of land cleared 5–15 years ago (ha)			
Year = 2000	110.8	-53.62	-157.5
	(296.0)	(471.8)	(435.2)
Year = 2005	1145.4***	1244.8***	1120.1***
	(416.9)	(380.5)	(331.5)
Year = 2009	940.7**	1077.8***	966.9***
	(416.3)	(408.1)	(369.1)
Area of land cleared <5 years ago (ha)			
Year = 2000	672.1	1016.8	961.4
	(472.9)	(731.8)	(723.7)
Year = 2005	2165.0*	2433.4***	2320.8***
	(1175.6)	(698.5)	(671.2)
Year = 2009	42.39	19.26	245.4
	(768.6)	(778.2)	(776.5)
Mature forest area (ha)			
Year = 2000	-175.4	-167.1	-163.4
	(295.5)	(546.7)	(520.1)
Year = 2005	996.4	924.4*	972.8**
	(622.6)	(492.2)	(461.3)
Year = 2009	2361.5***	2218.8***	2217.7***
	(492.3)	(583.5)	(545.8)
Observations	643	644	643
Adjusted R2	0.461		

Note: Standard errors in parentheses.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

land-year interactions. The results indicate that land values do indeed vary by both vintage and year. Neither the land use (i.e. forest or cleared) nor the individual vintages of the land are significant determinants of property value in 2000. In 2005 both land cleared more than 15 years ago and land cleared less than 5 years ago increase property value by approximately R$2000/ha, while both land cleared 5–15 years ago and forest land increase property value by approximately R$1000/ha. In 2009, the value of 'medium' vintage land is again lower than the value of 'old' land, although this difference is not significant (see Table 6 for significance of differences in coefficients by land vintage/use). Newly cleared land does not increase the value of the property in 2009, and forest land has an estimated value of over R$2000 across the alternative specifications.

When we compare across time periods, the value of each of the cleared land vintages rose between 2000 and 2005, and declined between 2005 and 2009 (Fig. 4). In contrast, the value of forest land rose from negative (although not significantly different from zero) in 2000 to around $1000/ha in 2005, to over R$2000/ha in 2009. Table 7 shows the significance of differences in the coefficients across time periods.

In principle, the market value of an individual property should not be affected by the personal characteristics of the household that currently owns the property. However, it is possible that the characteristics of the respondent or their household could influence their stated value of a property. We therefore estimate the same models as in Table 5 with additional explanatory variables to capture the demographics, education and origin of the respondent household. Table 8 shows that the inclusion of these household characteristics does not significantly alter

Table 6
p-values from F-tests of differences in coefficients from model of property value – differences in prices of 1 ha of different vintages in each year, based on estimation results in Table 4.

	Area of land cleared >15 years ago (ha)	Area of land cleared 5–15 years ago (ha)	Area of land cleared <5 years ago (ha)	Mature forest area (ha)
2000				
Area of land cleared >15 years ago (ha)	–	0.3871	0.4432	0.4441
Area of land cleared 5–15 years ago (ha)		–	0.1935	0.9927
Area of land cleared <5 years ago (ha)			–	0.2255
Mature forest area (ha)				–
2005				
Area of land cleared >15 years ago (ha)	–	0.0257	0.7615	0.0340
Area of land cleared 5–15 years ago (ha)		–	0.1199	0.8014
Area of land cleared <5 years ago (ha)			–	0.1165
Mature forest area (ha)				–
2009				
Area of land cleared >15 years ago (ha)	–	0.4835	0.1922	0.1217
Area of land cleared 5–15 years ago (ha)		–	0.4241	0.0489
Area of land cleared <5 years ago (ha)			–	0.0539
Mature forest area (ha)				–

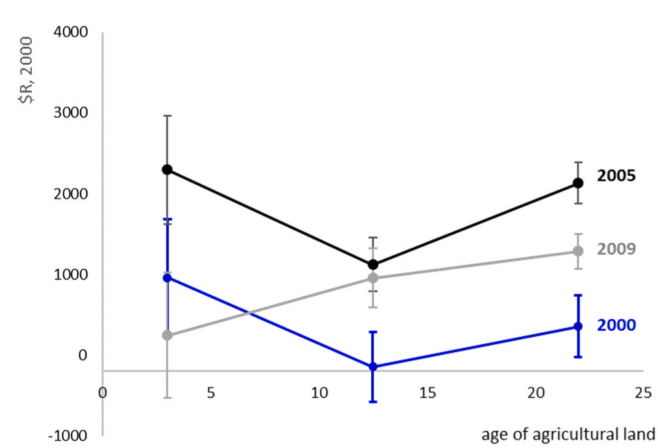

Fig. 4. Property value per hectare does not consistently decline with age according to fixed effects regressions. Standard errors noted with error bars, n = 351.

Table 7
p-values from F-tests of differences in coefficients from model of property value – differences in prices of 1 ha of each vintage between years, based on estimation results in Table 4.

	2000	2005	2009
Area of land cleared >15 years ago (ha)			
2000	–	0.000	0.0093
2005		–	0.0006
2009			–
Area of land cleared 5–15 years ago (ha)			
2000	–	0.0127	0.0437
2005		–	0.7436
2009			–
Area of land cleared <5 years ago (ha)			
2000	–	0.1613	0.5020
2005		–	0.0400
2009			–
Mature forest area (ha)			
2000	–	0.0741	0.0007
2005		–	0.0566
2009			–

Table 8
Marginal values of an additional hectare of cleared or forest land with household characteristics included in specification.

	(1) Pooled OLS-Year	(2) 2-level Mixed Effects-Year	(3) 3-level Mixed Effects-Year
Area of land cleared >15 years ago (ha)			
Year = 2000	227.9	200.5	235.5
	(354.6)	(416.5)	(378.4)
Year = 2005	1902.0***	1961.6***	1909.4***
	(317.1)	(338.0)	(253.2)
Year = 2009	1186.6***	1249.7***	1169.5***
	(217.8)	(304.8)	(212.4)
Area of land cleared 5–15 years ago (ha)			
Year = 2000	153.5	12.77	-80.51
	(307.1)	(465.0)	(427.2)
Year = 2005	1227.3***	1329.3***	1210.2***
	(417.3)	(375.4)	(325.7)
Year = 2009	1119.1**	1193.9***	1091.7***
	(436.1)	(400.7)	(361.4)
Area of land cleared <5 years ago (ha)			
Year = 2000	469.0	812.3	746.1
	(369.5)	(717.0)	(708.9)
Year = 2005	2131.4*	2285.1***	2216.9***
	(1202.1)	(684.3)	(656.0)
Year = 2009	-21.47	-11.92	199.1
	(682.5)	(761.2)	(760.0)
Mature forest area (ha)			
Year = 2000	-212.6	-215.7	-216.1
	(284.9)	(537.1)	(510.0)
Year = 2005	863.0	847.5*	880.2*
	(602.9)	(482.3)	(451.9)
Year = 2009	1956.9***	1880.7***	1866.6***
	(437.5)	(576.1)	(539.4)
Observations	642	643	642
Adjusted R^2	0.486		

Notes: Standard errors in parentheses. Household characteristics included in specification: family size, average age of male and female household heads, average years of education of male and female household heads, whether family migrated from most economically developed regions of Brazil (South or Southeast).
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

the estimates of the value of an additional hectare of cleared land of a given vintage or an additional hectare of forest land.

5. Discussion and conclusions

In this article, we examine the trajectory of values of cleared and forest land in agrarian settlements typical of those that have been established across the Brazilian Amazon. The Brazilian government pursued a policy of agrarian settlement in the Amazon region from the 1970s onwards, with the goal of poverty alleviation and regional development. Observers of the initial advance of the deforestation frontier in the Amazon argued that these settlements were not sustainable, because long-term agricultural production cannot be sustained on tropical soils once the initial nutrient gain from deforestation was depleted, and therefore settlers would quickly move on to the newest frontier. However, since a policy shift in 2004, the Brazilian government has sought to close the new deforestation frontier (through establishment of protected areas and increased monitoring and enforcement) while simultaneously promoting the intensification of agricultural production on the old frontier. Our study region of Ouro Preto do Oeste, which is part of this old frontier, has experienced declining deforestation rates, partly due to exhaustion of the forest stock, and partly due to rising standards of living associated with non-farm activities. We consider whether intensification may also be contributing to reduced deforestation and increased standards of living by examining changes in the value of agricultural and forest land.

We use hedonic methods to estimate the contribution of one hectare of cleared or forest land to the value of a frontier property and examine how this varies by the length of time since that hectare was initially deforested. We use year fixed effects to control for region-wide conditions that affect overall returns to land, and municipality and settlement fixed effects to control for potential correlation between the trajectory of land clearing and improvements in the settlements resulting from external investment, e.g. infrastructure improvements. This allows us to distinguish changes in land quality from the overall development of the frontier and wider changes in the economic and policy environment. It is also possible that property level investments could be correlated with the trajectory of land clearing. We therefore include both random effects for properties and variables capturing the quality, location and investments in the property, as well as the age of the property as a whole and deforestation of neighboring properties, in our models. Overall, our results suggest that land values do not systematically decline with the length of time since the land was initially deforested. Thus, if the productivity of agricultural land declines over time in the Amazon as has been widely assumed, this is outweighed in our study region by other factors that increase returns to that land. We also find that estimated values of all land vintages are consistently higher in 2005 than in 2000 or 2009. In contrast, the value of forest land increases over time.

In 2000, the real value of properties in our study region was lower than in later periods, and that value was not a function of the areas of land of different vintages. In the late 1990s, new INCRA settlements were being created, with new properties being allocated to incoming migrant households. Land was relatively abundant. Most households had larger properties than they could use in the short term so property size was not a significant determinant of its value. Instead, the main determinants of overall property value were the physical and geographic characteristics, specifically soil type and distance from the main urban center. The values of cleared land of all vintages and of forest land rose considerably between 2000 and 2005. This may reflect in part new perceived scarcity of land, due to a provisional change in the Brazilian Forest Code in 2001 that limited clearing to 20% of forested properties in the Amazon region, and a major policy shift towards forest conservation in 2004 under the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) (Soares-Filho et al., 2014). The newest land (cleared less than five years prior) adds the most per hectare to the value of the property in 2005, while land cleared between 5 and 15 years earlier is worth about half as much per hectare, suggesting substantial deterioration in productivity. However, the value of land cleared more than 15 years before 2005 contributes as much to property values as newly cleared land. It is possible that this is because the highest quality land was cleared first, although in that case we would expect to see a comparable pattern in the other years. Alternatively, it may be more beneficial or less costly to make investments that raise the productivity of the longest-cleared land than to invest in more recently cleared land. For example, if land was first cleared nearest to the road or house, the return to investments in that land will be higher than on land that is less accessible. In addition, our method for estimating land vintages does not allow us to account for whether land has been left fallow or reforested for any period. That could also raise land productivity and is most likely for the oldest land.

The biggest change observed over our 9-year panel is that between 2005 and 2009, the marginal value of newly cleared land declined to zero, while the marginal value of forest land doubled. This was a period of increased monitoring and enforcement of forest conservation policy in the Brazilian Amazon, building on PPCDAm. Specifically, in 2008, Federal Decree 6514 established new legal sanctions for violations of land use restrictions, including fines for illegal deforestation on private property (Santiago et al., 2018). In the same year, Resolution 3545 of the Brazilian Central Bank made access to subsidized rural credit conditional on compliance with titling and forest conservation requirements (Assunção et al., 2020). Compliance required a written plan for reforestation of areas that had been illegally cleared (Biggs et al., 2019). Thus, two of our survey waves (in 2005 and 2009) each occurred one year after significant policy regime shifts designed to protect the forest (Soares-Filho et al., 2014). Landowners appear to have interpreted these differently. Our estimation results suggest that in 2005, they were most concerned about restrictions on future clearing, making cleared land of all vintages more valuable. In 2009, our results suggest that they were more concerned about the costs of being out of compliance, such that the marginal value of forest land increased relative to the marginal value of cleared land.

Counter to conclusions made based on the physical characteristics of the soils alone, we do not find evidence that land values deteriorate over time after clearing. This is consistent with previous observations of ongoing improvements in living standards in our study region (Caviglia-Harris et al., 2016; Mullan et al., 2018). This may be due in part to unique factors in our study region, such as improvements in infrastructure and development of regional markets for agricultural outputs, especially milk. In addition, over the time period studied, there was increased enforcement of laws restricting deforestation. In particular, policy changes in both 2004 and 2008 increased the chances that illegal clearing would be detected and sanctioned. Comparing 2009–2005, we observe a large increase in the relative value of forest land and a reduction in the value of newly cleared land. This occurred in spite of agricultural development policies that raised the incentives to deforest. Our results suggest this effect was offset by policies that increase the relative value of forest land by conditioning public benefits (such as subsidized credit) on demonstrated compliance with forest conservation requirements, which could require investing in reforestation. However, our findings on the value of older land also highlight the tradeoffs between (a) raising agricultural productivity and incomes and (b) reforestation of degraded agricultural land. If efforts to sustain agricultural production are successful, the opportunity costs of forest restoration to fulfill Brazil's NDC for climate change mitigation or contribution to the Bonn Challenge (e.g. through Planaveg) will increase.

CRediT authorship contribution statement

Katrina Mullan: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing, Visualization. **Jill Caviglia-Harris:** Conceptualization, Methodology, Investigation, Data curation, Writing, Visualization, Funding acquisition. **Erin Sills:** Conceptualization, Methodology, Investigation, Data curation, Writing, Funding acquisition.

Declarations of interest

None.

Acknowledgments

This research was funded by the National Science Foundation, USA, under Grants SES-0752936, SES-0452852, SES-0076549 and BCS-1825046. We thank Dan Harris of Salisbury University for providing the figures, GIS analysis, and the land cover variables, and Dar Roberts at the University of California, Santa Barbara for providing the land cover classifications.

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