Land Use Policy 58 (2016) 456–471

Contents lists available at ScienceDirect

Land Use Policy

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

Evolving frontier land markets and the opportunity cost of sparing forests in western Amazonia

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ARTICLE INFO

Article history:
Received 11 June 2015
Received in revised form 20 June 2016
Accepted 11 August 2016
Available online 18 August 2016

Keywords:
Land use and land cover change
Colonization
Deforestation
Conservation
Payment for ecosystem services
Peru

ABSTRACT

Efforts aimed at sparing forests on tropical forest frontiers through REDD+, PES or conservation initiatives currently rely on a limited understanding of the operation of land markets and their effects on the opportunity cost of forests as frontiers develop. In this paper, we draw on a unique dataset of landholder-reported land transactions that includes post-1991 land sales-in three sub-montane frontier forest areas on the eastern slopes of the Peruvian Andes. We analyze reported land sales that took place between 1979 and 2013 among Amazonian frontier farmers and find highly active land markets in all three areas, often in the absence of formal land tenure. As frontiers developed, parcel size fell, as did the portion of remaining forest cover, and land prices rose, reflecting both forest clearing and general land price inflation as the areas became more populated and developed. Across three study districts in 2013, each additional hectare of forest cleared raised the expected price of a parcel of land by US $1371–$2587. Importantly, we estimate the opportunity cost per hectare of frontier forest rose markedly over time: by $124–$226 per year between 2003 and 2013, a rate of increase over that period of 9–27% per year. Forest conservation programs that rely on estimates of landholders' willingness to accept compensation for sparing forest need to take into account that these values change rapidly as frontiers develop.

1. Introduction

Conserving tropical forests requires an understanding of the economic incentives that operate on the agricultural frontier. Land markets play an important role in shaping the incentives faced by frontier actors: prices for land are a deciding factor in whether a frontier area is profitable to settle and they determine incentives for forest clearing (Bowman et al., 2012; Chomitz et al., 2005; Poffenberger, 2009). As land prices increase, the pressure to deforest intensifies as farmers bring more of their land into agricultural production in order to recoup the initial investment; forest left standing therefore represents a forgone opportunity to farmers. The opportunity cost of standing forest is important in the planning of forest conservation efforts, particularly for initiatives aimed at reducing emissions from deforestation and degradation (REDD) and for payments for ecosystem services (PES) schemes (Fisher et al., 2011b; Naidoo and Adamowicz, 2006; Plumb et al., 2012). A higher opportunity cost of standing forest increases the minimum payments that landholders would be willing to accept to conserve forests (Börner et al., 2010; Wunder, 2007).

Few studies to date have investigated land prices in tropical frontier areas. In newly-settled frontier areas, record-keeping on land transactions can be non-existent or spotty at best (Gould et al., 2006; Sills and Caviglia-Harris, 2008). In Latin America, studies on rural land markets have either focused on more developed non-frontier areas (Chomitz et al., 2005; Zegarra, 1999a) or used national surveys that lack information on individual land transactions (Deininger et al., 2003, 2004). To overcome the limitations imposed by scant data on land transactions, researchers have used landholders' stated perception of land value (Merry et al., 2008; Sills and Caviglia-Harris, 2008; Zegarra, 1999a). Alternately, land values have been estimated without reference to land markets by using net present value (NPV) estimates of future agricultural production (Börner and Wunder, 2008; Fisher et al., 2011b; Naidoo and Adamowicz, 2006).

In frontier Amazonia, several consistent predictors of land price have been found among previous studies. First, distance to market depresses prices because of the increased cost of transporting farm inputs and outputs. Second, farmer investment in land parcels in the form of forest clearing or pasture or crop establishment

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http://dx.doi.org/10.1016/j.landusepol.2016.08.015
0264-8377/

increases land value; forest coverage on land parcels is generally associated with lower prices per hectare (Chomitz et al., 2005; Merry et al., 2008; Sills and Caviglia-Harris, 2008). In one report from Pará, Brazil, pasture was reported to be five to ten times more valuable than the same area of forestland (Mertens et al., 2002). Total area of land parcels and slope have been shown to negatively affect the price per hectare (Chomitz et al., 2005; Sills and Caviglia-Harris, 2008). Merry et al. (2008) found that length of the landholder's residence time is positively associated with land price, but-perhaps surprisingly-holding definite title to the land did not affect landholder perceptions of value.

Land prices increase as frontiers advance, and this affects incentives for future land use and forest clearing (Sills and Caviglia-Harris, 2008). Expectations of rising land price encourage land speculation, leading individuals to acquire larger areas of land and clear more forest than they would considering only the productive potential of the land (Naidoo and Adamowicz, 2006; Poffenberger, 2009). Speculation thus plays a key role in accelerating the rate of frontier advancement and associated deforestation (Carrero and Fearnside, 2011; Fearnside, 2002; Kirby et al., 2006). The relative importance of speculative versus productive motivations may change through time as frontiers develop (Carrero and Fearnside, 2011; Fearnside, 2005). It is also important to note-particularly where land speculation is common-that land markets do not depend on the presence of formal land title. Indeed, land markets in Latin America have been described in areas where the proportion of individuals who hold formal title to their land ranges from 18% (Carrero and Fearnside, 2011) and 27% (Merry et al., 2008) to 71% (Alvarado, 1994) and 76% (Zegarra, 1999b).

Forest frontiers are advancing rapidly in many parts of the Amazon Basin. The 'arc of deforestation' in the southeast of the Basin is the locus of most deforestation; however, rates of deforestation in parts of the western Amazon, on the eastern slopes of the Andes, are just as high as rates in the southeast (Fig. 1). Twenty percent of the deforestation in Amazonian countries between 2000 and 2012 took place in the five countries that span both the Amazon and

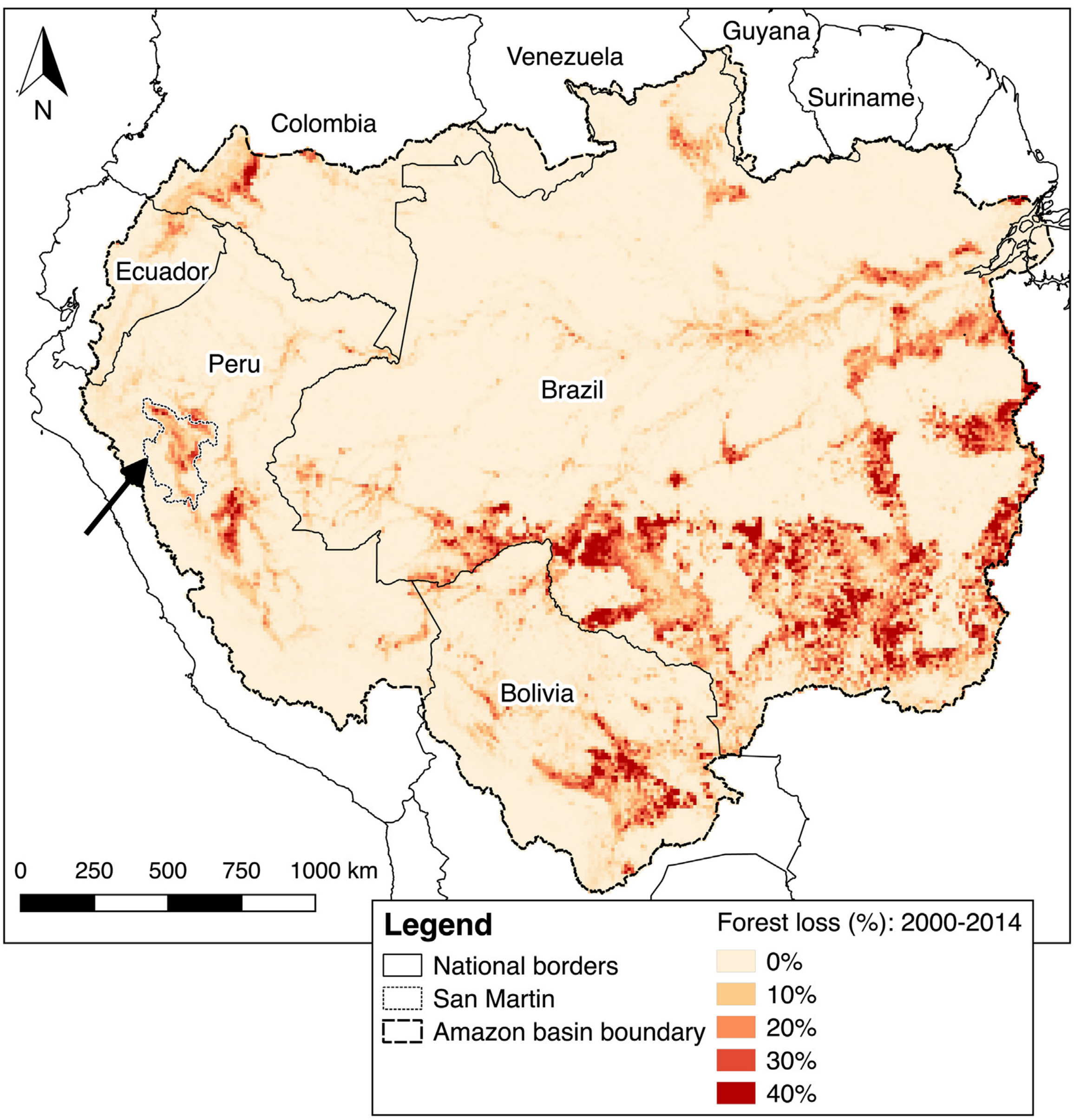

Fig. 1. Deforestation in the Amazon Basin between 2000 and 2014 mapped at six minutes resolution (1/10th of a degree; about 10 km) using data from Hansen et al. (2013). Greyscale in legend indicates total forest loss as a percentage of land area over the 2000–2014 period (i.e., percent of pixels in the original 30 m by 30 m resolution dataset that recorded a transition from forest to non-forest). Region of San Martin indicated by dotted border and by arrow.

the Andes-Bolivia, Colombia, Ecuador, Peru, and Venezuela (Hansen et al., 2013). Peru has the fourth-highest volume of above-ground carbon of any country in the world (Saatchi et al., 2011) and land use change in Peru is estimated to contribute 0.8 gigatonnes of carbon to the atmosphere in the next decade (Asner et al., 2014). Forest loss in the western Amazon is also of great concern for biodiversity: the eastern slopes of the Andes have one of the highest levels of species endemism on Earth and are consistently identified as a priority area for biodiversity conservation (Brooks et al., 2006; Swenson et al., 2012).

The processes driving forest loss on either side of the Amazon basin are distinct. Large-scale soya and pasture-responsible for much of Brazilian deforestation-are far less prevalent on the Andean slope (Bradley and Millington, 2008; Eakin et al., 2011; Gay et al., 2006; Morton et al., 2006). Coffee and coca are better adapted to the higher elevations of the Andes than the lowland Amazon and both play an important role in the development of the region (Muschler, 2001; Schroth et al., 2009; UNODC ICMP, 2007). Population composition in the western Amazon also differs from that in the southeast; colonization by Andean migrants who move eastwards into Amazonia is a common dynamic documented in Bolivia (Killeen et al., 2008; Müller et al., 2011; Paneque-Gálvez et al., 2013), Colombia (Sanchez-Cuervo and Aide, 2013), Ecuador (Pichón, 1997; Rudel and Horowitz, 1993) and Peru (Bebbington and Bury, 2009; Ichikawa et al., 2014; Shanee et al., 2015). The high proportion of Andean migrants among frontier colonists in the western Amazon creates a distinct cultural context which may influence land use; place of origin and cultural background are important determinants of agricultural practices (Parry et al., 2010; Redo, 2013). Differences in crops, agricultural scale, and demographic patterns between the western Amazon and the Brazilian Amazon require us to adjust our understanding of the processes of land cover change for each region. Importantly, we know much less about land use change and the drivers of deforestation in the western Amazon than we do about the Brazilian Amazon. This is particularly true in Peru where most field-based research along the eastern slopes of the Andes was halted for more than a decade due to political instability and violence in the 1980s and 1990s (Kent, 1993).

This study analyzes land sales and other types of land acquisitions (claims, grants, inheritances, gifts) that were reported by landholders to have occurred between 1968 and 2013 in three frontier areas on the eastern Andean slopes of Peru. Few published studies as yet report data on individual land transactions in rural Latin America, and to our knowledge this is the first study for a recently-settled frontier. We identify the determinants of land prices using a hedonic pricing model and use land sale data to evaluate land holding changes through time. We then combine these two elements of our analysis-the evolution of parcel characteristics and the pricing model-to assess the changing opportunity cost of forest sparing in each of the three frontier areas. Our findings advance understanding of the economic incentives driving frontier deforestation, particularly in the Andean Amazon, and inform the design of forest conservation and PES programs.

2. Study area

The study was conducted in three frontier districts of San Martin, a region of Peru that borders the Amazonian Regions of Ucayali and Loreto, and the Andean Regions of Huanuco, La Libertad, and Amazonas. San Martin encompasses 51,253 km^2 of territory and elevations range from over 4000 m above sea level (masl) on the western border down to 200 masl near Yurimaguas in the lowland Amazon (NASA-JAXA, 2009). San Martin had a population of 806,452 in 2013, of which 23.7% lived either in Tarapoto, the largest city and commercial center, or in Moyobamba, the regional capital (INEI, 2013). The region has a Y-shaped network of principal highways with the northeastern branch connecting to the river-based transport of the Amazon while the northwestern and southern branches lead to cities on the coast (Fig. 2). The first road to connect San Martin to the coast is the northwestern route that was completed in 1974.

The flat, central valleys of San Martin were settled more than a century ago and in these areas rice and corn are the most widespread crops. Cattle raising occurs throughout the region, but ranching in San Martin is less economically important than agriculture: producers earn 10.6 times as much from growing coffee in San Martin than they do from selling beef (MINAGRI, 2013; MINAGRI, 2014). At higher elevations, coffee is the dominant crop. San Martin is the second-largest producer of coffee in Peru after the Region of Junin, producing 22% of the national total in 2012 (MINAGRI, 2013). Coffee in San Martin is most prevalent in the upper parts of the secondary valleys that branch from the region's central valleys and principal roadways (Fig. 2). Coffee-particularly the higher-quality *arabica* variety-performs poorly at low elevations; peak yields have been reported at 1500 m in Mexico, while in most areas production below 700 m is significantly compromised relative to higher elevations (Muschler, 2001; Schroth et al., 2009). These higher-elevation zones are the focus of most frontier expansion in San Martin and have the highest rates of forest loss in the region. Overall, deforestation rates in San Martin have been very high-on the order of 1.12% or 574 km^2 per year during the late-1980s-a higher rate than any Brazilian state (Perz et al., 2005). Analyses of more recent deforestation data published by Hansen et al. (2013) indicate that from 2000 to 2012, San Martin had the third-highest proportion of its land area deforested of all first-level administrative areas in the Amazon basin after the Brazilian states of Rondonia and Mato Grosso (Holland, 2016).

Frontier expansion in San Martin is closely linked to migration from other parts of Peru, as migrants move from more heavily populated areas in the Andean *sierra* in search of cheaper, more abundant land in the Amazon (MINAGRI, 2013; Schjellerup, 2000). In the 1970s, agrarian reform programs actively encouraged Andean farmers to colonize parts of San Martin (Schjellerup, 2000); no such government policies exist today, but rates of in-migration to San Martin remain high. In 2007, 19% of the population of San Martin had moved from another region within the previous five years; this was the third-highest rate of in-migration among Peru's 25 regions (INEI, 2014).

For this study, we worked in three areas of San Martin that were settled at different times: the Districts of Pardo Miguel, Shamboyacu, and Alto Biavo (Fig. 2). The study areas are similar to each other in two respects. First, they all overlap the buffer zone of one of two protected areas, the Alto Mayo Protected Forest in the case of Pardo Miguel and the Cordillera Azul National Park in the cases of Shamboyacu and Alto Biavo. Second, coffee is the predominant cash crop in the three areas: 93% of interview respondents in this study reported growing coffee, and for 41%, coffee was their only source of cash income. The three districts have different histories of settlement and development, but all three were first settled after infrastructure establishment: highway construction in Pardo Miguel in the mid-1970s and logging activities in Shamboyacu and Alto Biavo in the mid-1990s and 1998–2003, respectively.

Early settlers in each of these areas on the frontier acquired land through land claims. Peruvian law allows an individual to claim possession of state-owned rural land if he/she has made economic use of the land for at least one year prior. Individuals can also claim legal rights of possession to land that was previously privately owned; however, in this case the putative land holder has to demonstrate economic use over five years (*Ley del registro de predios rurales-Decreto legislativo No. 667;* 1991, modified 1996, 1997,

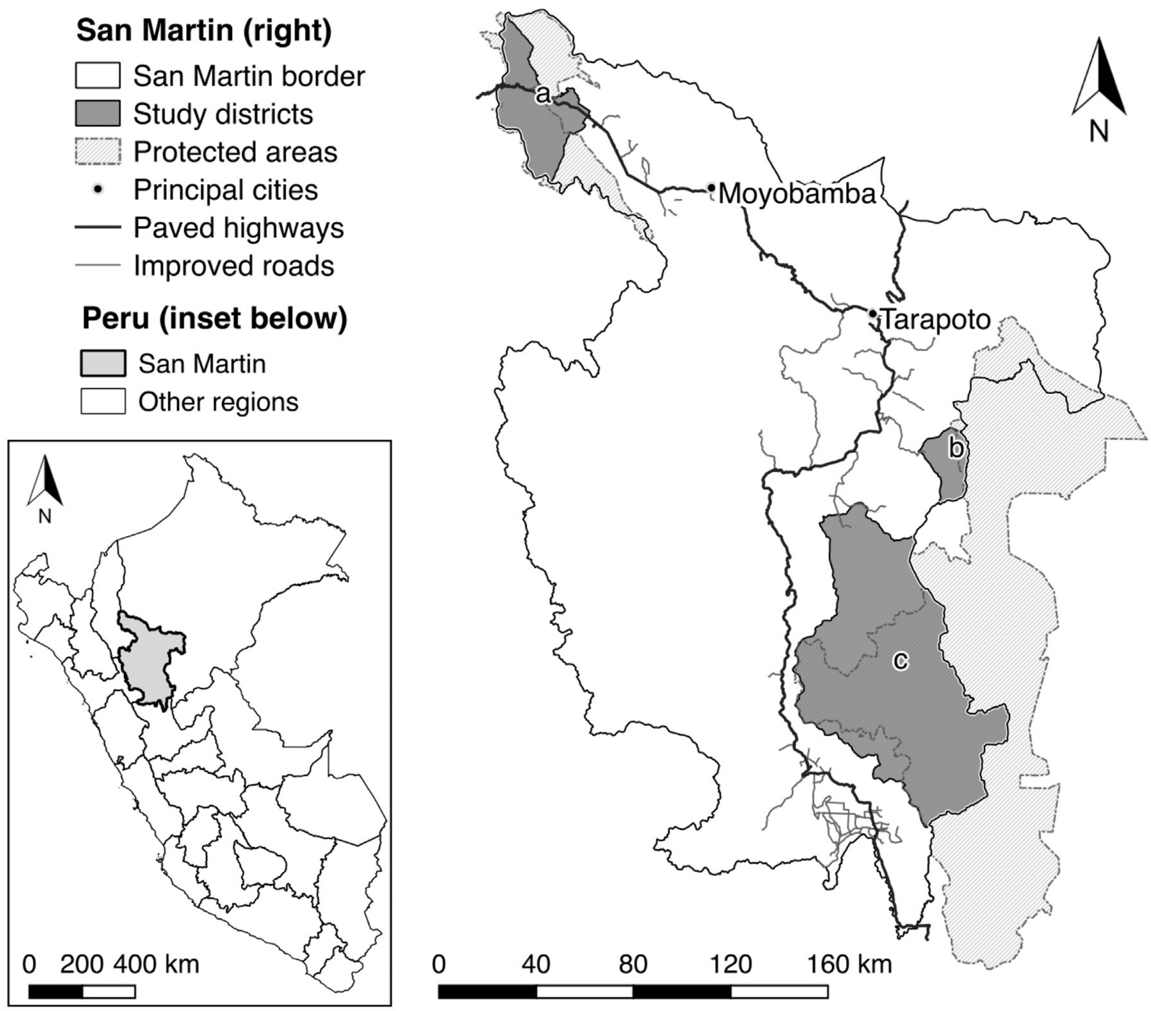

Fig. 2. Region of San Martin shown within Peru (inset map on left). San Martin with study districts indicated in dark grey (main map on right). Districts are (a) Pardo Miguel, (b) Shamboyacu, and (c) Alto Biavo. "Improved roads" are any roads that have a non-dirt (generally gravel) surface but that are unpaved. Region-wide data on seasonal dirt roads is not available. San Martin is divided into 77 districts, but for clarity of presentation the map only indicates the three study districts. Protected areas indicated are those in whose buffer zones the study areas are located: Alto Mayo Protected forest (northwestern part of San Martin) and Cordillera Azul National Park (east of San Martin).

1998, 1999, 2006) (FAO, 2014). In addition to formal land rights, a well-established cultural convention gives customary rights to *posesionarios*: individuals who bring previously uncultivated land into agricultural or livestock production. This convention can be more important than the law itself in frontier areas where the Peruvian state and regional government agencies have limited monitoring and enforcement capacity.

Approximately 30% of agricultural land in San Martin is held by registered land title (Conservation International, 2011; Gobierno Regional de San Martín, 2009; ProCeja, 2011). However, most formally-titled land is found in the large central valleys and in our recently-settled study areas land title is much less common. In land transactions where no formal land title is involved, purchase agreements (*documentos de compra-venta*) define the land parcel and the selling price. These documents are signed by both buyer and seller as well as by a community authority-the municipal agent or the lieutenant governor-or a justice of the peace. The documents are generally kept by buyers and accumulate as land parcels pass through multiple owners with new purchase documents drafted for each transaction. In this way, the act of sale itself legitimates a claim by initiating a paper trail that establishes the land parcel as a legal entity.

NGO staff and regional government officials report that "land trafficking" (*trafico de tierras*) is common in San Martin. This is a particularly aggressive form of land speculation whereby well-connected individuals and groups claim large tracts of land that are generally beyond the administrative reach of local and regional governments (Conservation International, 2011; ProCeja, 2011). Speculators seek to profit by selling the land to new migrants, piece by piece; in some cases, they actively recruit migrants from outside communities, often from distant districts in the *Sierra*.

3. Methods

We collected reports of land sales and of other types of land acquisitions that took place in three frontier districts of San Martin. The districts were selected following three criteria: that each be an area of active deforestation; that each be a site of active forest conservation efforts; and, that the districts collectively represent a range of settlement times. Interviews conducted in 2011 with NGO and government staff established that the districts best fitting these criteria were those bordering the Cordillera Azul national park in eastern San Martin, and those bordering on the Alto Mayo protected forest in the region's northwest. Information on the history of settlement of each district led us to select the District of Pardo Miguel in the northwest as an older frontier area-first settled in the mid-1970s-and the Districts of Shamboyacu and Alto Biavo along the Cordillera Azul as newer settlement areas. The upper valley of the district of Alto Biavo-an area separated from the rest of the district by a high ridge and lack of road links-was specifically identified by NGO and government staff as the most recent and active frontier area in San Martin with the fastest rates of in-migration and frontier expansion in 2012 and 2013. Shamboyacu has a settlement history that is intermediate between Pardo Miguel and Alto Biavo: the expansion of settlement peaked in Shamboyacu in the late-1990s and early-2000s. We interviewed landholders in three communities in Pardo Miguel, six in Shamboyacu, and four in Alto Biavo. We chose to work in communities within the protected area buffer zones that had active and community-specific forest conservation activities sponsored by one of two large NGOs working in the districts.[1] In all three districts, we defined a "community" as a cluster of households with a government-funded school and at least one teacher. In the upper valley of Alto Biavo and in the district of Pardo Miguel, we worked in communities situated inside the protected area buffer zone but outside the protected area itself, i.e., four and three communities, respectively. In Shamboyacu, the official buffer zone of the protected area is exceptionally large-it extends beyond the border of the district to include areas that have been dedicated to commercial farming for several decades. We therefore restricted our sampling to the area in the district that was a higher priority for local conservation efforts: the side closest to the National Park. The district is situated in a river valley with one side of the valley sloping upwards to the Park border. We worked in six of the seven communities on the park-side slope (in one community, authorities declined participation), but not those in the valley bottom or on the opposite slope.

3.1. Household interviews and land transaction data

Reports of land sales and of other types of land acquisition events were extracted from semi-structured interviews with 193 randomly-selected households in 13 communities in our study districts. To select households, we first mapped all occupied homes within a 30-min walk of each community center. We systematically numbered houses on the map and used a regular increment from a random starting number to ensure that sampling was geographically representative across each community. We sought to interview either twenty percent of the households in each community or twenty households in the more populous communities where twenty percent would have required an unrealistically large number of interviews. We met this sampling goal in 11 out of 13 communities and fell slightly short in two communities (i.e., 17 households, 14%; 14 households, 18%-see Table S1).

In order to maintain focus on the lands surrounding study communities, we excluded land parcels that were more than a 60-min walk from the community center. Within that 60-min boundary, respondents reported 261 past land sales-in which they were either buyer or seller-as well as 64 other land acquisitions that were not land sales (i.e. that did not involve any payment). These other 64 land acquisitions were either land claims (26); land grants from community authorities or regional government (10, Alto Biavo only); or inheritances and gifts from family members (28). Of the 261 land sales, 249 took place after 1991 when Peru's present currency-the Nuevo Sol-was introduced. For our analysis of land prices, only these 249 are included; pre-1991 land sales were subject to high annual rates of inflation (up to 7482%) which complicated any analysis of prices. We asked landholders to report details on each land parcel they had acquired or sold since arriving in the community. For each land parcel involved in a sale or in another type of land acquisition, landholders reported the following: the total area, land cover composition (percent by type), the year of the transaction, and in the case of land sales, the sale price. Landholders also described the location of the land parcel using local landmarks and travel times. For each parcel sold, we calculated the travel time to the nearest paved road (in all cases, the nearest paved road was the principal regional highway) in the year of each land sale. These calculations were based on reported travel times on footpaths and on GPS-tracked distances for all roads. We adjusted these travel times to reflect what they would have been in the year of the land sale by using information from long-time community residents on dates of road construction and road improvement. We mapped parcel locations using descriptions from landholders and GPS data on local footpaths and waypoints that we created in the field. Because locations were not precise, we assigned each land parcel to one of 39 different clusters; we then calculated average elevation and slope within a one-kilometer buffer as a proxy for the elevation and slope on individual parcels. We used digital elevation maps with 30 m resolution (NASA-JAXA, 2009) to calculate slope and elevation metrics.

As an additional indicator of the level of social development in the area surrounding each land parcel, we also account for the distance between land parcels and the nearest primary school in the year of the land sale. To evaluate access to education, we obtained data from San Martin's regional education directorate on the location and date of establishment of every school in the region and then used GIS to evaluate the Euclidean distance to the closest primary school for each parcel at the time of sale.

3.2. Estimating determinants of land price

Factors that affect land price differ in the extent to which they change through time as well as in the degree to which landholders are able to influence them. Elevation and parcel location are both time-invariant. Other factors change through time but in a manner over which landholders have little or no control; these include commodity prices, travel time to market, and the level of development of communities in the area (e.g., access to educational or health services). Commodity prices vary internationally in a way that is largely unpredictable to landholders whereas travel time and community development tend to evolve unidirectionally and somewhat predictably as the frontier develops: travel times shorten as infrastructure improves and communities usually accrue more services as populations increase. The final set of factors that affect land price, over which landholders do exert control, are those relating to land cover on the parcel. With sufficient labor and/or capital, landholders can clear forest and convert land either to agricultural crops or pasture.

We used two different statistical approaches to evaluate the relative importance of factors determining land price following hedonic theory (Rosen, 1974). First, following the hedonic literature (c.f. Malpezzi, 2008), we build a series of models to ultimately estimate the following relationship:

$$ln\left(V_{ijt}\right) = \alpha + \beta_1 X_{ijt} + \beta_2 L_{ij} + \beta_3 D_j + \beta_4 T_t + \varepsilon$$

where V is the value per unit area of land parcel i in district j at time period t, X represents parcel and neighborhood characteristics that may vary over time, L is a set of location characteristics that do not vary over time (e.g., slope and elevation), D represents time-invariant factors common to all parcels within a district, T accounts for the time period in which the land transaction is observed, and ε is the error term. The data used to estimate this relationship are discussed below.

[1] The primary NGOs managing conservation programs in these two areas are Conservation International in the Alto Mayo Protected Forest and the Centro de Conservación, Investigación y Manejo de Areas Naturales (CIMA) in Cordillera Azul National Park.

To represent *V*, previous work in the Amazon has used the total price of land parcels (Merry et al., 2008) or the total lot price and the price per hectare (Sills and Caviglia-Harris, 2008). Here we use price per hectare to evaluate prices relative to a constant quantity of land and for consistency with many studies of rural property values outside the Amazon (Bastian et al., 2002; Chomitz et al., 2005; Snyder et al., 2008; Xu et al., 1993; Zegarra, 1999a). We use inflation-adjusted log-transformed land price per hectare as our dependent variable, and restrict our analysis to sales that occurred after the current currency, the Nuevo Sol, was established in 1991 (prior to this Peru went through a period of hyperinflation that peaked in 1990 at an annual rate of 7482%, and land prices during that period were likely influenced by a different set of social, political and economic forces). For the 1992–2013 sales (n = 249), we corrected all prices ($US) for inflation to a 2013 base year using annual inflation data recorded by the Central Reserve Bank of Peru (IMF, 2012).

To capture time-varying parcel and neighborhood characteristics represented by *X*, we collected a set of parcel-level characteristics at the time of sale including lot size and the percent of land in specific land uses (forest, coffee, pasture, agriculture, and fallow). Percent cover in primary forest reflects farmer investment in the land parcel, i.e., less forest cover corresponding to greater investment, and land cover characteristics are known to have significant effects on land price (Busch and Vance, 2011; Casetti and Gauthier, 1977; Chomitz et al., 2005; Merry et al., 2008; Sills and Caviglia-Harris, 2008).

Neighborhood characteristics in *X* include variables related to market access following traditional land-rent theory (Ricardo, 1891; Von Thünen, 1966), which highlights how travel time fundamentally affects land prices, land use, and rural landscape differentiation. In our case, we used distance to schools, a measure of village centrality and local infrastructure development, and travel time to the nearest paved road. Access to education is an important indicator of frontier development as it is highly valued by households in rural Peru (Gertler and Glewwe, 1990) and has been shown to play a role in decisions to migrate to and from agricultural frontiers (Carr, 2009). As an indicator of market access we use travel time to the nearest road instead of to a specific market because agricultural goods are sold in different towns. The paved highways in San Martin are in good condition, meaning that the most significant differences in transport expense are from farm to highway rather than on the highway itself. Importantly, our measures of travel time and distance are specific to the year of sale. Time-invariant location variables in *L* include slope and elevation. *D* is simply a set of district-level dummy variables.

To represent structural changes that might relate to time *T*, it is important to take into account different histories of settlement in our three frontier areas since we might expect absolute time trends to be different in each district. In order to account for this difference in onset of development in each district, we constructed *T* as the number of years a land transaction occurs after the first land sale reported in each district in our dataset, i.e., 1979, 1996, and 2001 in Pardo Miguel, Shamboyacu, and Alto Biavo, respectively. This helps standardize the onset of development across the three districts.[2] The hedonic literature most often includes dummy variables for the year of sale (Abbott and Klaiber, 2011; Hansen, 2009; Ma and Swinton, 2012; Nappi-Choulet et al., 2007; Pope, 2008; Swoboda et al., 2015) with the interest of controlling for structural changes in land markets over time. We follow the literature and estimate the effect of time with a dummy variable approach. However, given our interest in exploring land market dynamics, we want to see how land values change over time in the frontier setting. Thus, following Horsch and Lewis (2009) (as we empirically justify below-see the end of Section 3.2 and Supplementary Fig. S1) we also explore a continuous measure of time. However, a continuous measure of time imposes a linear relationship between time and land prices, which may mask non-linear structural changes in market conditions. Therefore, when using the continuous time measure we also include commodity prices as macro-economic factors that have been shown to influence land use and rates of forest clearing (Barona et al., 2010; Verburg et al., 2014). For commodity prices, we included inflation-corrected prices for coffee and cattle as these are most relevant locally: our respondents reported anecdotally that land prices increased in years when the price of coffee was high. Our data on live cattle prices are specific to San Martin and come from the Peruvian Ministry of Agriculture and Irrigation (MINAGRI, 2014).[3] MINAGRI data on San Martin coffee prices are incomplete and so we use international arabica coffee prices as a proxy (IMF, n.d.). For the years during which there is overlap between the San Martin and the international coffee price data, the correlation between the two is high ($r = 0.97$; $p < 0.001$), so the latter serves as a reasonable proxy. In order to evaluate potential non-linear effects of the year of sale on land prices, we also include a quadratic term for the year of the land sale.

In these regression frameworks we compare for fit with R^2 and for parsimony (as well as fit) with the Akaike information criterion (Akaike, 1974; Burnham, 2004; Mac Nally, 2000). Land parcels are spatially clustered; slope and elevation are calculated as averages for the locale around parcel locations rather than individually for each parcel. To avoid biased standard errors that may arise with OLS regressions (Moulton, 1990), we used robust regression modeling with clustering. We present four models with various specifications.

In the four models we evaluate, the parameter coefficients represent the marginal contribution of that parameter toward the value at the time of sale. In all cases we include dummy variables for districts Shamboyacu and Pardo Miguel (the reference is Alto Biavo). For each model, we evaluated the spatial autocorrelation of the residuals to assess the need to use a spatially-explicit regression. We calculated Moran's I of the residuals of our models using a weights matrix based on a threshold distance. Because we have no a priori theoretical reason to select a particular threshold distance within which neighboring parcels may be correlated with each other, we evaluated Moran's I for our fully specified model using a range of different threshold distances in order to determine the threshold distance at which we observe the maximum level of spatial correlation or dispersion (Dubé and Legros, 2014). The set of distances we tested included the minimum distance for which each observation would have at least one neighbor (5.56 km) and each 10 km increment from 10 km until 100 km, at which point a land parcel would be considered a "neighbor" of every other land parcel in its district. We found that the highest absolute value for Moran's I at a threshold distance of 10 km; however, at no distance was the absolute value of spatial autocorrelation or dispersion greater than 0.016 (Fig. S2). Using the 10 km threshold where the maximum absolute Moran's I value was observed in our fully specified model, we also evaluated Moran's I of the residuals for each of the partially-specified models. We report these Moran's I values below in our regression tables. Still, few are statistically significant and none are of a magnitude that indicates worrisome spatial clustering, so we employ simple OLS models here that are not spatially explicit.

[2] Models that use 'year' do not qualitatively differ from the results presented below

[3] Cattle prices from 2005 to 2013 are online (MINAGRI, 2014), while historical data starting from 1991 were provided to us via correspondence with MINAGRI staff. These data are available from the authors upon request.

Our first model of land price, following Sills and Caviglia-Harris (2008), estimates the sale price of a parcel of land simply as a function of travel time to market. The second model incorporates parcel-level variables in X_{ijt} including the total size of the land parcel, the percent covered in various land uses (the reference is coffee), and L_{ij} the average elevation and slope of the surrounding land (within a buffer of one kilometer). In our third model, we added information on neighborhood characteristics and include year-level dummy variables for T_t to capture temporal structural changes (cf. Horsch and Lewis, 2009).

Our fourth model includes a continuous and squared variable for year as well as temporally explicit estimates of coffee and cattle prices. Although we have no a priori reason that changes over time would operate linearly, when plotting the year-dummy coefficients from model 3 in chronological order (see Fig. S1), the plot suggests a linear trend in which land prices increase over time. Thus model 4 includes a continuous linear specification of the time variable to attempt capturing the variation in our data in a parsimonious way and help us see the average time trend in land prices in this frontier region. Model 4 additionally accounts for potential macro-structural economic changes with market commodity prices.

Following regression modeling, we use hierarchical partitioning to evaluate the individual contribution of each significant independent variable to the explained variance in price per hectare. Hierarchical partitioning considers all possible model constructions given a set of variables. We restrict the hierarchical partitioning analysis to variables that are significant in the full OLS model described below; due to software limitations on the number of variables that can be included (13) in hierarchical partitioning.

We conducted our regression analysis with clustered standard errors in Stata version 14.1, our assessment of Moran's I in GeoDa version 1.6.7, and our hierarchical partitioning analyses in the 'hier.part' package of R version 3.2.2.

3.3. Estimating the opportunity cost of forest sparing

In order to examine the opportunity cost to landholders of forest sparing, we use model 4 from the OLS regressions described above to predict two values for each land sale that involved a parcel of land that had some standing forest (179 of the 249 total land sales). The first value was simply the predicted value of sale price for each land sale. The second value we calculate is the predicted price of each of the 179 land sales if the forest cover on the parcel of land in question was reduced by one hectare. By subtracting the second value from the first, we recover an estimate of the average expected increase in a sale price that a landholder could expect by clearing an additional hectare of forest.

4. Results

4.1. Land markets

Land markets in the three frontier areas arose only once there was little or no remaining land available for claiming (i.e., within one-hour's walk from community). The maximum amount of time during which land claims and land sales occurred contemporaneously in a given community was four years. In seven of 13 communities, the period of overlap between land claims and land sales in our sample was one year or less. Combining all of the study communities within a given district, the maximum period of overlap between land claims and land sales was eight years. Once land markets were established, land sales or inheritances became the only way people acquired land. The transition from claims to sales had occurred by 1980 in Pardo Miguel, by 2001 in Shamboyacu, and by 2009 in Alto Biavo (Fig. 3).

More than half of the individuals in our sample (52.8%) reported participating in land markets in the five years prior to being interviewed. A large majority participated in land markets (86.4%), defined as buying or selling land, at some point since their time of arrival in the study community. Participation in land markets in the previous five years ranged from a high of 60.3% in Shamboyacu to a low of 47.5% in Pardo Miguel (Table 1). In all districts, at least twice as many households had purchased land as had sold land. This difference was even more pronounced in the more recently-settled Districts of Shamboyacu and Alto Biavo: 56.4% and 42.9% of households purchased land in the previous five years, respectively, whereas only 7.7% and 7.1% of households sold land in the same time period (Table 1). Households tended to acquire the majority of their land soon after their arrival in the area; of longer-term resident households who had lived in the study community for ten years or more, the land that they acquired (claimed, inherited, granted, or purchased) in the first two years after their arrival represented 52.2%, 52.6%, and 66.1% of the total household landholdings in Pardo Miguel, Shamboyacu, and Alto Biavo, respectively.

4.2. Forest coverage and parcel size

Land parcels that survey respondents reported claiming or being granted tended to be larger than average holdings and were typically covered entirely by primary forest. Of recorded land claims ($n = 26$) and land grants ($n = 10$), 78% were land parcels of twenty hectares or more (mean = 23.6 ha, $\sigma = 13.6$ ha). Parcel size of claimed land and granted land was broadly consistent across the three study districts with sample means of 31.0 ha ($\sigma = 41.0$ ha), 21.7 ha ($\sigma = 14.9$ ha), and 23.8 ha ($\sigma = 10.8$ ha) in Pardo Miguel, Shamboyacu, and Alto Biavo, respectively. Regarding the coverage by primary forest, excluding only one outlier event, the remaining (35) parcels had greater than 90% coverage in primary forest; the balance of 10% (or less) comprised small patches of fallow land created by farmers who had later abandoned the land. Parcel sizes and forest coverage in the parcels that were claimed were significantly higher than averages among parcels that were bought or sold (cf. Table 1).

Over time, parcels sold became progressively smaller and less forested. This occurred in the transition from land claims to land sales, but also during the period when only land sales occurred. The year of sale and the percent of forest cover overall are negatively correlated in each of the three districts as is demonstrated by OLS models using year of sale as a predictor of percent forest cover. These effect of year on forest cover was significant at $p < 0.05$ in Pardo Miguel ($\beta = -2.77$; $p = 0.002$) and in Shamboyacu ($\beta = 3.29$; $p < 0.001$) whereas it was marginally significant in Alto Biavo ($\beta = -2.49$; $p = 0.074$). In Pardo Miguel, the average proportion of forested land on each land parcel sold declined from 52.9% in the 1990s to 31.2% in the 2000s to 15.7% in the period from 2010 to 2013. Shamboyacu and Alto Biavo showed similar declines on a decadal comparison although they started from higher average levels of forest cover (Table 1). Most forest cover loss has been due to the expansion of coffee plantations (Table 1; Fig. 4). Pasture and non-coffee agriculture have also expanded at the expense of forest; however, these land covers represent less than one third of the extent represented by coffee plantations in each district, and in many cases represent much less.

As with forest cover, the size of parcels decreased through time across all three districts. The year of sale and parcel size were significantly negatively related in Shamboyacu ($\beta = -0.75$; $p < 0.001$) and in Alto Biavo ($\beta = -1.65$; $p = 0.004$). In Pardo Miguel, the relationship showed the same sign but was not significant at $p < 0.05$ ($\beta = -0.19$; $p = 0.069$). In Pardo Miguel, the average parcel sold was 6.6 ha between 1992 and 1999, 2.7 ha in the 2000s, and 3.7 ha between 2010 and 2013. In Shamboyacu this decline was from

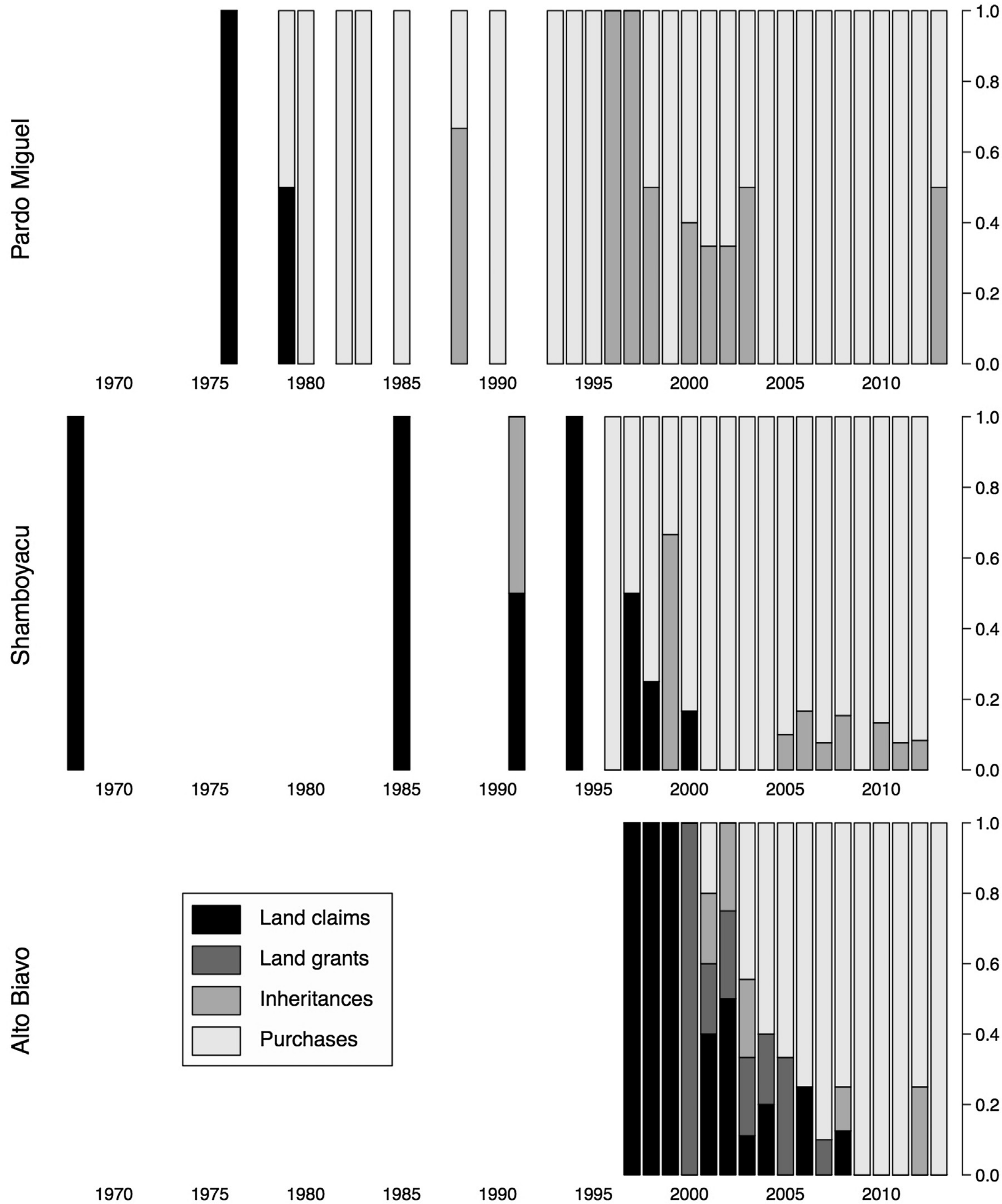

Fig. 3. Proportion of total land acquired by each method as it changed through time in each of the three districts. This includes land purchases/sales (261 in total; 249 that took place since the establishment of Peru's current currency in 1991), informal land claims (26), land grants (10, Alto Biavo only), and inheritances or gifts (28).

12.9 ha to 6.8 ha to 3.0 ha while in Alto Biavo there was a slight drop from 13.3 ha to 12.2 ha between the 2000s and 2010s (Table 1). With declines in both parcel size and the proportion of forest, the total area of forest on each parcel sold declined through time in all districts (Fig. 6I).

4.3. Estimates of sale price

Reported land sales that took place between 2010 and 2013 had inflation-adjusted average prices of $671 per hectare in Alto Biavo, $1340/ha in Shamboyacu, and $1596/ha in Pardo Miguel. These all reflect increases from the 1990s when prices in Shamboyacu and Pardo Miguel were $131/ha and $433/ha and land markets had not yet arisen in Alto Biavo (Table 1). The 19 variables used in our final estimation of land prices (model 4) explain 73% of variance in the log-transformed price per hectare of land (R^2).

Model 1 simply tests the relationship theorized by Von Thünen that land further from market will be cheaper; the only independent variable included is the travel time to paved road which has a strongly negative effect on land price ($p < 0.001$). Travel time alone explains about 31% of the variation in land price per hectare. Model 2 additionally accounts for parcel-level X_{ijt} and location-level L_{ij} variables, which doubles the explanatory power of the model to 63%. In this model, most variables hold significant explanatory

Table 1
Household participation in land markets and characteristics of land parcels bought or sold. Values in parentheses are standard deviations. Only post-1991 land sales are included in this table (n = 249) as those are the only ones for which reliable price data are available.

Unit	Variable	Pardo Miguel	Shamboyacu	Alto Biavo
Households (n = 193)		*n* = 59	*n* = 78	*n* = 56
	% who in the previous five years...			
	purchased land	37.3%	56.4%	42.9%
	sold land	15.0%	7.7%	7.1%
	purchased or sold land	47.5%	60.3%	48.2%
	% who since arriving in community...			
	purchased land	79.7%	85.9%	64.3%
	sold land	21.7%	15.4%	10.7%
	purchased or sold land	86.4%	88.5%	67.9%
Land parcels bought or sold post-1991 (n = 249)		*n* = 68	*n* = 125	*n* = 56
	Travel to paved road (minutes)	35.9 (19.0)	180.9 (33.5)	312.8 (66.9)
	Elevation (masl)	1258.6 (147.6)	810.5 (175.4)	914.2 (127.3)
	Number of sales recorded by decade			
	1992–1999	8	9	0
	2000–2009	37	80	41
	2010–2013	23	36	15
	Parcel size by decade (ha)			
	1992–1999	6.6 (7.4)	12.9 (21.8)	–
	2000–2009	2.7 (2.1)	6.8 (8.1)	13.3 (11.7)
	2010–2013	3.7 (5.7)	3.0 (2.8)	12.2 (11.2)
	Forest cover by decade (%)			
	1992–1999	52.9 (49.0)	80.0 (32.6)	–
	2000–2009	31.2 (42.2)	76.3 (33.9)	93.6 (17.7)
	2010–2013	15.7 (27.3)	38.1 (44.1)	71.9 (40.7)
	Coffee plantation by decade (%)			
	1992–1999	3.0 (4.4)	11.1 (33.3)	–
	2000–2009	38.9 (41.7)	10.4 (23.9)	1.4 (6.3)
	2010–2013	45.9 (39.3)	25.7 (38.0)	23.0 (41.1)
	Price per hectare (2013 USD)[a]			
	1992–1999	433.3 (265.0)	130.9 (172.1)	–
	2000–2009	1188.8 (1254.4)	499.4 (908.3)	275.7 (539.7)
	2010–2013	1595.8 (733.5)	1340.4 (1111.0)	670.6 (862.5)

[a] Adjusted for inflation to equivalent of 2013 US dollar values. Calculated from price in Peruvian Nuevo Soles (PEN) at the time of sale, converted to 2013 PEN value using Peruvian annual inflation rates (IMF, 2012), converted to USD using the 2013 average exchange rate (1.00 USD = 2.71 PEN).

power except several land cover estimates, and the land parcel's slope. All estimates are of the expected sign: travel time, the total number of ha, and percent in forest cover (relative to coffee) are negatively associated with land value. Elevation and percent in cacao are positively associated with land sale price.

In models three and four, we look at two different ways of incorporating time into the analysis. Model 3 uses a dummy variable for each year, consistent with the hedonic literature, in which discrete controls capture structural and annually-specific changes. Compared with model 2, model 3 shows nearly equivalent relationships among all the variables while goodness of fit characteristics (R^2, AIC) improve. Parcel size, slope, and percent forest cover have strongly significant negative associations with land price per hectare while elevation has a significant positive association with price. Plotting the year-dummy coefficients chronologically (see Fig. S1) suggests a linear trend in which land prices increase over time. Thus model 4 includes a continuous linear and squared term for time. Although the R^2 decreases slightly in model 4 relative to model 3 (0.711 and 0.723, respectively), estimates of the parameters of interest remain unchanged. AIC slightly favors model 3, but values are very close (576.5 in model 3 as compared to 577.5 in model 4). We use model 4 (with the continuous measure of time, as opposed to the dummy-variable version in model 3) as the preferred model to simplify analysis and interpretation below.

We compared the effect in model 4 of a one standard deviation change in each significant predictor variable (Table 3). A one standard deviation increase in travel time (106.3 min), parcel size (9.4 ha), percent forest cover (43.4%), percent fallow cover (28.7%), or slope (4.0%) was associated with, respectively, 50.9%, 18.3%, 46.3%, 18.5%, and 12.6% decreases in the price of land per hectare (percentage changes presented here because dependent variable is log-transformed). Conversely, a one standard deviation increase in elevation (247 m), percent cacao cover (6.8%), or coffee price ($1191/tonne) increases land prices by 43.6%, 3.9%, and 16.1%, respectively. The terms relating to the year of sale indicate that land prices increasing most rapidly in the early years after the establishment of land markets, followed by slowing increases and eventually a possible decline, i.e. following a quadratic function. The coefficients predicted by the model suggest a peak in land prices 33 years after the first land sale in the district. We also tested models using interaction terms between the continuous year variable by districts and percent forest cover, and our interpretation of the land markets remain unchanged from those in model 4 (see results in Supplementary Table S2). With the main effects from model 4 included as well as interaction terms involving the district and the year of sale as well as forest cover and year of sale, the R^2 value improved slightly–less than one percent–from model 4 (Table 2) to 0.733; however, the Akaike Information Criterion was higher in models that included the interaction terms (579.4–583.7) than in model 4 (577.5), suggesting less parsimonious models.

We used hierarchical partitioning to determine the relative contribution of each significant variable from Model 4 to the overall variance in land price per hectare. This technique compares the contributions of each variable independent of model selection (Mac Nally, 2000). Hierarchical partitioning indicated that the largest contributors to the variance in land price were the variables relating to land cover that together explained 38.7% of the independent variation explained in the model. Percent of land in fallow and percent of land in forest, both having negative effects on land price, explain 13.1% and 12.7% of independent variation, respectively, whereas percent of land in cacao-having a positive effect on price-explains 13.1%. After the land cover variables, the next largest contributor

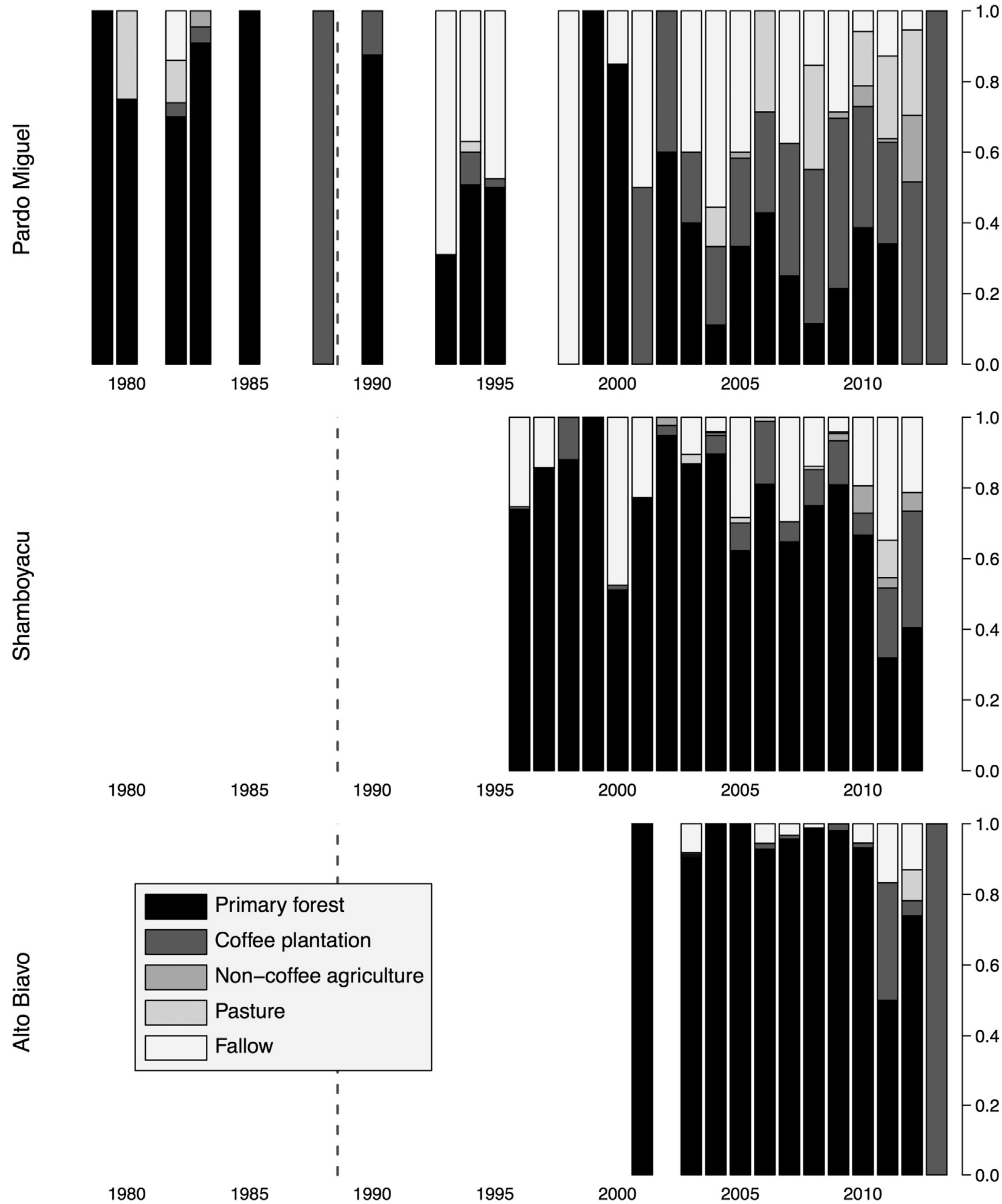

Fig. 4. Proportion of the total amount of land sold in a given year that was under each land cover type. Includes all reported land sales that occurred within a one-hour walk of study communities (n = 261). Sales that were included in land price models because they date from after the 1991 introduction of Peru's current currency (Nuevo Sol) are those to the right of the dotted line (n = 249).

was the year of sale relative to the first sale in the district, which had a positive effect on land price and contributed 11.5% to the total variation explained by the models. When the quadratic form of the same variable is included (9.0%), the total variation explained by the two terms relating to the year of sale is just over one fifth of the total variation explained by the model (20.4%). The remaining variables, in descending order of their contribution to overall variance, are parcel size (9.3%), travel time (8.6%), coffee price (6.6%), elevation (5.2%), Alto Biavo district dummy (5.1%), slope (3.1%), and Shamboyacu district dummy (3.0%) (Fig. 5).

4.4. Predicting the effect of forest clearing on land price

Of 249 land sales analyzed in our regression models and hierarchical partitioning, 179 had some amount of forest cover (Fig. 6I). For these land parcels, we predicted how the sale price would have changed if the parcel had one hectare less of forest (this value was scaled if there was less than one hectare to begin with). Using data from each land sale and coefficients from our preferred regression model (model 4, Table 2), we predicted the expected price of each sale and compared it with a hypothetical expected price after one additional hectare of forest clearing (Fig. 6II). In any given year,

Table 2
OLS models with cluster-robust standard errors for 2013 sale price per hectare (log-transformed US dollars).

	Model 1	Model 2	Model 3	Model 4
(Intercept)	7.147***	5.993***	2.707**	3.247***
	(−52.28)	(−13.95)	(−3.40)	(−4.74)
Travel time to paved road (minutes)	−0.011***	−0.006**	−0.007***	−0.007***
	(−4.36)	(−3.01)	(−4.75)	(−3.98)
Size of land parcel (ha)		−0.037***	−0.030***	−0.021**
		(−6.40)	(−3.74)	(−2.83)
Primary forest (% cover)		−0.018***	−0.014***	−0.014***
		(−8.06)	(−7.41)	(−7.64)
Cacao (% cover)		0.014***	0.008**	0.006*
		(−4.53)	(−3.36)	(−2.18)
Other crops (% cover)		0.000	−0.004	−0.005
		(−0.03)	(−1.51)	(−1.83)
Pasture (% cover)		0.004	0.006	0.003
		(−0.72)	(−0.95)	(−0.48)
Fallow (% cover)		−0.008***	−0.007*	−0.007***
		(−4.10)	(−2.67)	(−3.89)
Other land cover (% cover)		0.004	0.006	0.002
		(−1.56)	(−1.60)	(−0.58)
Elevation (masl)		0.002***	0.002***	0.001***
		(−7.06)	(−5.73)	(−4.67)
Slope		−0.034*	−0.015	−0.034**
		(−2.35)	(−1.04)	(−2.76)
Distance to primary school (km)			0.002	−0.004
			(−0.07)	(−0.11)
Coffee price (arabicas; USD/tonne)				0.000*
				(−2.03)
Cattle price (USD/tonne)				0.000
				(−0.07)
Years after first recorded sale in district				0.170***
				(−6.31)
Years after first recorded sale in district (squared)				−0.003***
				(−3.74)
District: Shamboyacu	0.709	1.306***	2.354**	2.265***
	(−1.70)	(−4.62)	(−3.52)	(−6.38)
District: Alto Biavo	1.319	1.679**	3.198***	3.062***
	(−1.66)	(−3.36)	(−4.55)	(−5.60)
Dummy variables for individual years included?	No	No	Yes	No
R^2	0.312	0.630	0.774	0.731
Adjusted R^2	0.304	0.611	0.723	0.711
AIC	785.2	647.0	576.5	577.5
Moran's I of residuals	−0.0113	−0.0129*	−0.0126	−0.0131*
N	249	249	249	249

Significance levels indicated as follows: *** < 0.001 < ** < 0.01 < * < 0.05.

Table 3
Effects on land price per hectare of each significant predictor variable as estimated by coefficients of model 4 in Table 2. The increment of change in each independent variable is equal to one standard deviation of the distribution in that variable in the overall sample.

Variable	Increment (One σ)	Predicted effect on land price per hectare
Travel time to paved road (minutes)	106.3	−50.9%
Size of land parcel (ha)	9.4	−18.3%
Primary forest (% cover)	43.3	−46.3%
Cacao (% cover)	6.8	3.94%
Fallow (% cover)	28.7	−18.5%
Elevation (masl)	247.1	43.6%
Slope	4.0	−12.6%
Coffee price	1191	16.1%
Years after 1st sale	9.2	376.5%
Years after 1st sale (squared)	84.1	−19.4%

the potential gain in price from clearing one additional hectare of forest was greatest in Pardo Miguel and least in Alto Biavo. In 2013, the predicted increase in land sale price for each additional hectare of forest cleared was $2263, $2587, and $1371 in Pardo Miguel, Shamboyacu, and Alto Biavo, respectively. We found that in all three districts, the expected increase in land price from one additional hectare of cleared forest was itself increasing through time, curvilinearly. Wald tests indicated that the quadratic function had significantly better goodness-of-fit than did the linear function ($\chi_1 = 16.5$; $p < 0.001$). Examining these relationships in each district for the decade from 2003 to 2013, we found that the increase in land price expected from an additional hectare of forest clearing itself increased at an average annual rate of between $124 and $226. In Pardo Miguel, the expected price increase per additional hectare of forest cleared rose from $948 in 2003 to $2263 in 2013 (adjusted $R^2 = 0.39$; $p < 0.001$), or by $131 per year. Over the same period, expected price increases in Shamboyacu and Alto Biavo rose from $327 and $130 per hectare to $2587 ($226 per year; adjusted $R^2 = 0.70$; $p < 0.001$) and $1371 ($124 per year; adjusted $R^2 = 0.23$; $p < 0.001$), respectively. In annualized terms, these increases in the opportunity cost of forest sparing ranged from 9.1% in Pardo Miguel to 23.0% and 26.6% in Shamboyacu and Alto Biavo, respectively.

5. Discussion

We analyzed land sales in three frontier areas of San Martin, Peru and found that transacted land parcels became smaller and less forested over time. The reduction in the total amount of forest on land parcels, coupled with increasing land prices, has meant that

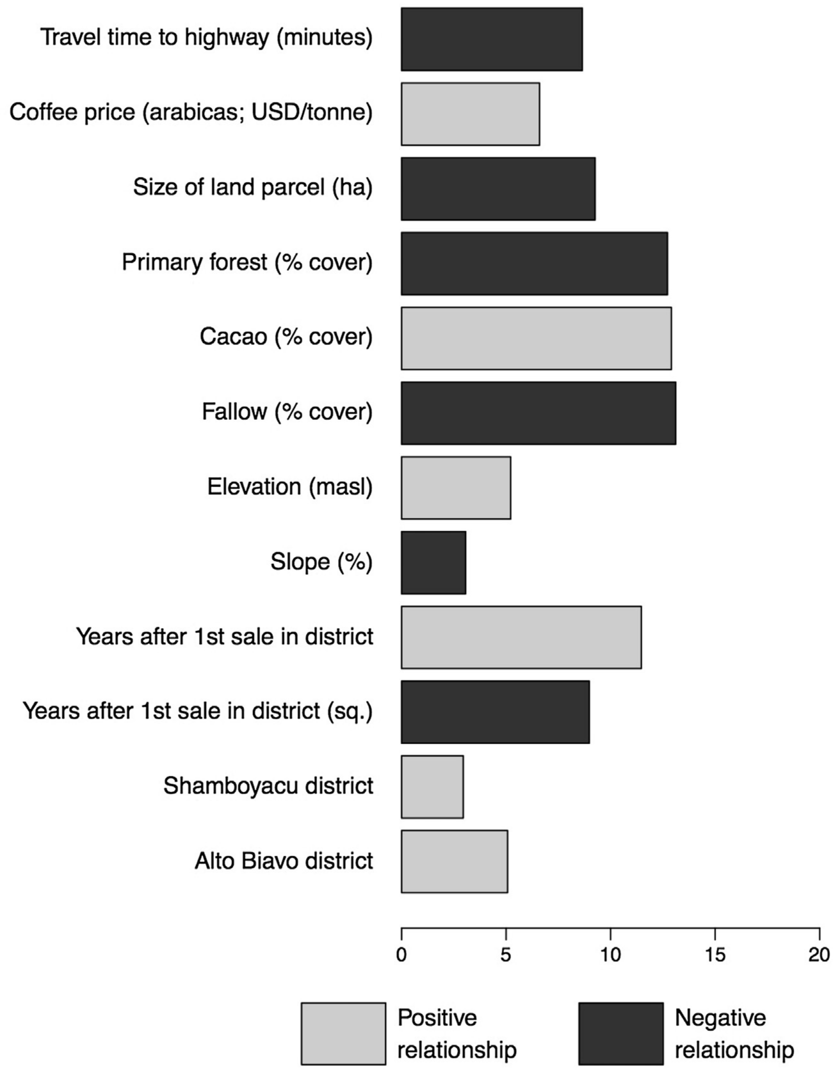

Fig. 5. Results of hierarchical partitioning on the prediction of land price per hectare (inflation corrected; log transformed) showing the proportion of all independent effects that can be attributed to each variable. All significant variables from model 4 (Table 2) were included. Color-coding of bars indicates whether the relationship between the variable and land price is positive or negative in the regression model, while values on the horizontal axes are the independent effect of each variable expressed as a percentage of total variance explained in the model by independent effects.

the financial incentive for forest clearing has increased steadily as these areas have developed. These patterns were consistent across three study districts, with a considerable lag between the earliest settled District of Pardo Miguel and the most recently settled District of Alto Biavo: average values for forest cover and parcel size for the years 2010–2013 in Alto Biavo were at levels seen in Pardo Miguel prior to 1990 (Table 1). Similarly, the predicted increase in land sale price from clearing one hectare of forest-an indicator of the opportunity cost to a land seller of leaving forest standing-was US $1371 in Alto Biavo in 2013, similar to the price increase expected in Pardo Miguel in 2007 or in Shamboyacu in 2009. In 2013, the expected increase in sale price from clearing forest was $2263 per hectare in Pardo Miguel and $2587 per hectare in Shamboyacu.

5.1. *Active markets in the absence of formal tenure*

Participation in land markets in our study communities-even in the absence of formal land title-was higher than reported in previous studies of rural land market participation elsewhere in Latin America. In the five years prior to interviews, 46.6% of respondents in our study communities bought land and 9.8% sold land (Table 1). No other study we could find of rural land markets in Latin America reported rates of market activity as high as those we observed. Studies from Colombia, Nicaragua, and coastal Peru found five-year participation rates in land markets that ranged from 1.1% to 13.5% (Alvarado, 1994; Deininger et al., 2003, 2004). The striking difference in land market participation between our study and previous work is likely due to the high proportion of newly-arrived individuals in these frontier communities: 92% of our respondents were born elsewhere in Peru and 60% had arrived in their communities in the previous ten years. As discussed in Section 4.1, the majority of land eventually acquired by longer-term resident households (ten years residence or more) was acquired in the first two years after their arrival in a study community. If households generally secure most land soon after their arrival, then communities with a high proportion of new arrivals (as is the case in our study communities) will have a high proportion of individuals participating in land markets. The high level of land market activity in these areas-and in other areas that are similarly dominated by in-migration and rapid demographic change-indicates that land prices and land price changes play a particularly important role in landholder decision-making. Land market dynamics deserve close attention in the design of programs and policies seeking to influ-

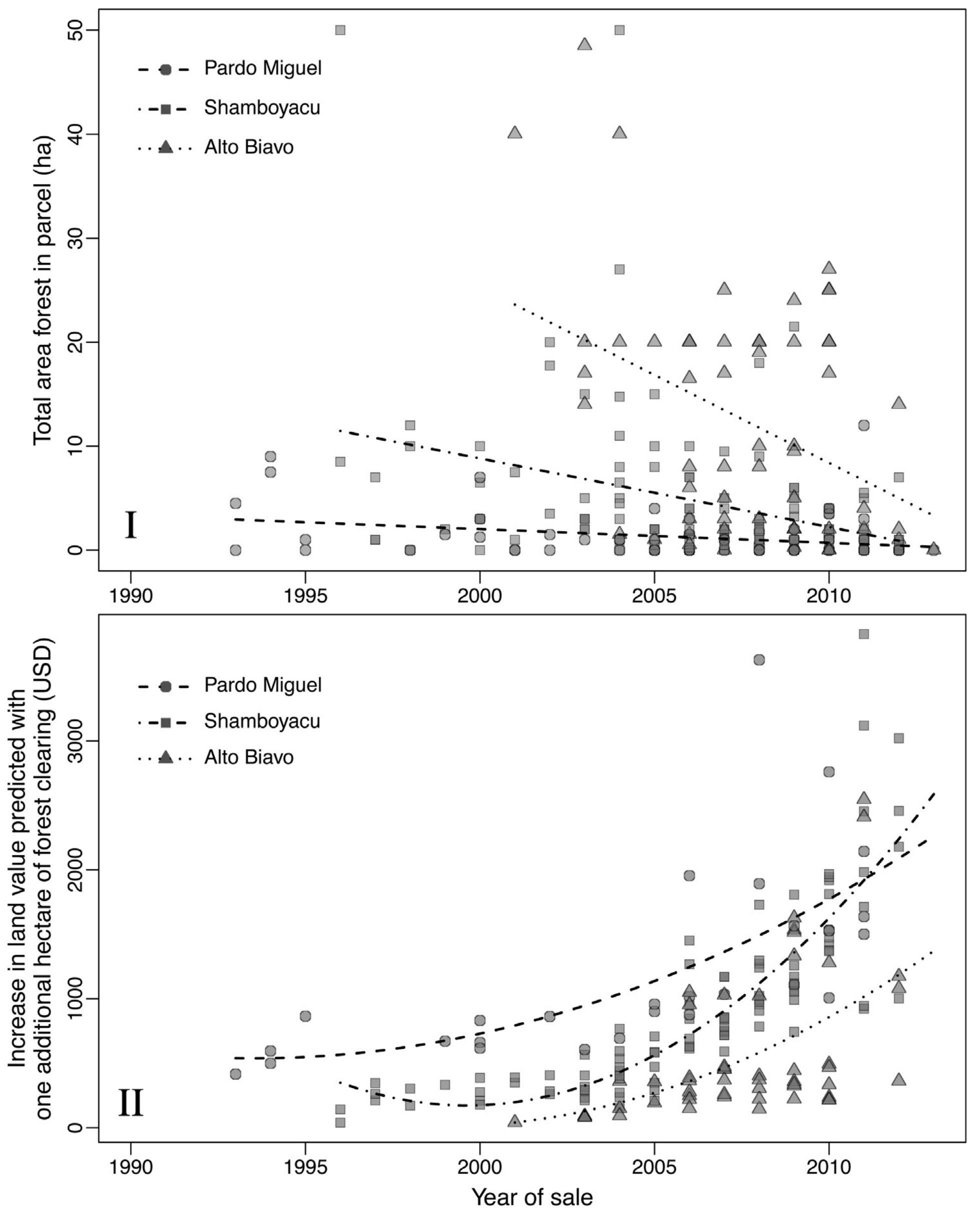

Fig. 6. (I) Total amount of forest cover on land parcels sold through time. Points with zero forest cover (shaded grey in color figure) indicate sales of land parcels that contain no forest; these are excluded from plot II. (II) The opportunity cost of forest sparing as indicated by the expected increase in the price of a land parcel that would be associated with the clearing of one additional hectare of land (modeled using the coefficients of model 4 in Table 2). The opportunity cost increases through time in all three districts but is generally higher in the longest-settled district (Pardo Miguel) and lowest in the most recently-settled district (Alto Biavo). Quadratic best-fit lines for the relationship between opportunity cost and the year of sale suggest that opportunity costs in Pardo Miguel, Shamboyacu, and Alto Biavo have increased by $131/year, $226/year, and $124/year respectively during the decade from 2003 to 2013. Values in 2013 would have been $2263, $2587, and $1371 (same order). All dollar values are US and inflation-corrected to 2013.

ence land use decisions-particularly regarding forest clearing-in developing forest frontier areas.

Formal land title is not a pre-requisite for active land markets. In our study, we found high levels of participation in land markets despite only 2% percent of respondents holding registered title. Formal land title may make markets more efficient and encourage the entry of different actors into land markets (Fearnside, 2005), but the absence of title does not prevent endogenous formation of a land market. Rather than inhibiting land markets, the lack of formal title in our study may in fact have provided additional incentive for transactions to take place. Because purchase agreements between buyer and seller often represent the first legal document relating to a land parcel, the act of selling can itself improve the security of the land holding by establishing a paper trail that proves a financial investment in the land. There are thus advantages to both the original claimant and to the person to whom they sell the land: the initial claimant will have made a quick financial return with the sale while the first buyer improves future tenure security. The use of a land sale to establish a paper trail is a different method of securing a claim than the method often required by land law-demonstrating productive use through forest clearing or establishment of crops. The fact that landholders may use land markets to improve their tenure security without clearing additional forest is a possibility that should be considered in the design of forest conservation policy or in the establishment of PES programs.

This study provides additional support to previous findings that rural land values are negatively affected both by standing forest cover and by travel time to market in Amazonia (Merry et al., 2008; Sills and Caviglia-Harris, 2008). Our results indicate larger effects than those found in the Brazilian Amazon. Whereas Sills and Caviglia-Harris (2008) report coefficients suggesting that a 25% decrease in forest cover would result in a price increase of 8.5–9.9%, we find that such a decrease corresponds to a 43.2% increase in land price. Our models indicated the fastest rates of land price increase in the first years of market establishment, after which rates of increase gradually declined. The maximum rate of increase, 18.2% in the first year after market establishment, was somewhat higher than the range of annual land price increases of 3–15% reported by Carrero and Fearnside (2011) from Brazil. This pattern of rapid initial increases suggests that the timing of land sales matters most early in the development of a frontier area, i.e., who arrives first and is able to acquire their land earliest. As the frontier develops, the issue of timing becomes less important and characteristics of the land parcel-characteristics that the landholder can modify through investment of time and money-become more important in determining land value. Rapid early returns mean that incentives for land speculation are highest in the first years after frontier establishment, suggesting that policy efforts to reduce deforestation during the early years of frontier establishment would do well to prioritize the reduction of speculation. Fearnside (2005), while describing high rates of land speculation in the Brazilian Amazon in the 1970s and 1980s that declined in the 1990s, suggested specific taxation regimes to deter land speculation. In San Martin, there is broad recognition among NGOs and government agencies of the role that land speculation plays in frontier expansion. However, efforts to reduce speculation and land trafficking have been relatively unsuccessful, in some cases because of the reportedly direct involvement of municipal-level officials in land trafficking (ProCeja, 2011).

5.2. *The cost of not clearing forest*

As parcels became smaller, less forested, and more expensive per hectare, the opportunity cost of standing forest increased. Higher total expenditures at the time of land sale make it more difficult for households to recoup their investment in land without expanding their crops or pasture further into the remaining forest. By showing the expected increase in land price resulting from one additional hectare of cleared forest, our models provide a proxy for the opportunity cost of forest sparing. Our estimates reflect the expected return to a land buyer who purchases a parcel of land, clears one hectare of forest, and then re-sells the parcel under the same market conditions of purchase (Fig. 6II). This does not include the cost to the landholder of forest clearing, so it should not be taken as the direct gain from clearing a hectare of forest; however, given relatively constant costs of forest clearing through time, increases in the expected price increase after forest clearing indicate higher opportunity costs of forest sparing. Our estimates show average annual increases in the opportunity cost of forest sparing of US $131, $226, and $124 per hectare of forest over the decade of 2003–2013 for Pardo Miguel, Shamboyacu, and Alto Biavo, respectively.

Whereas we have used land transaction data to estimate the opportunity cost of forest sparing, most studies have determined these costs by calculating the net present value (NPV) of future returns to agriculture. Despite differences in method, our estimates of US $1371 to $2587 per hectare are in a similar range to reported NPV-based values. In Tanzania, in a context of small-scale agriculture and charcoal production, the opportunity costs of forest sparing ranged between $1000 and $7000 per hectare with a median value of about $1700 (Fisher et al., 2011b). Studies in Brazil, Ecuador, and Bolivia have shown NPVs based on agricultural production range from $300/ha to $1100/ha for different crop types with one outlier of more than $3000/ha for soybean in Brazil (Börner and Wunder, 2008; Ferraro and Kiss, 2002; Grieg-Gran, 2008; Knoke et al., 2009; Vosti et al., 2002; Wunder, 2007).

One challenge of NPV-based methods for opportunity cost estimation is the fact that NPV is very sensitive to the discount rate used (Naidoo and Ricketts, 2006; Stern, 2007). Because our method follows a revealed-preference approach that focuses on the moment of land transaction, it does not depend on the selection of a discount rate. More importantly, by estimating the opportunity cost at one moment-as opposed to an NPV approach that estimates the value of land use over a long time frame-our approach allows us to track change in opportunity cost through time. This is an important contribution to land use and conservation planning, in particular for any program or policy operating in a fast-changing frontier environment. At the observed rate of change, the opportunity cost of sparing one hectare in the recently-settled District of Alto Biavo could catch up in six years to the cost observed in 2013 in the longer-settled District of Pardo Miguel. This rate of change illustrates how a conservation project that offers payments for avoided deforestation to landholders could be economically attractive to participants at the stage of project design but could cease to be attractive-and therefore effective-some years later as the frontier develops. This is of particular concern for programs that use direct forest-sparing contracts with farmers or market-based incentives (Ferraro and Kiss, 2002; Wunder, 2007).

Asner et al. (2014) estimate that the Alto Mayo Protected Forest (bordering Pardo Miguel) averages 57.9 tonnes of aboveground carbon per hectare while the Cordillera Azul National Park (bordering Shamboyacu and Alto Biavo) holds 92.0 tC/ha. These carbon densities would result in emissions of 211 and 336 tonnes of CO_2 per hectare in a scenario of clearing and complete conversion (converting from C to CO_2). Assuming that the forests in our study areas bordering these protected areas are of similar average quality to the forests within the protected areas, we can use these values to estimate the emissions from forest conversion. If a landholder in Pardo Miguel in 2013 could sell a parcel of land for $1836 more after forest clearing, and clearing released 211 tonnes of CO_2, then avoiding those emissions has an opportunity cost to the landholder of $8.82 per tonne, not accounting for the cost of forest clearing itself. In Shamboyacu and Alto Biavo those values would be $5.42 and $2.84. For comparison, the Stern Review (Stern, 2007) estimated that 50% of global deforestation could be avoided for a cost of about $5 per tonne. Other reported values have been higher: from $10-$21 per tonne for 50% of global deforestation (Kindermann et al., 2008) to above $40 in areas where conservation competes with high value crops such as oil palm (Fisher et al., 2011a).

While the opportunity cost per tonne of avoided emissions may be sufficiently low to be promising, we caution proponents of market-based conservation strategies in forest frontier areas. Market-based incentives have the potential to incentivize in-migration to the target area which risks the perverse outcome of increasing local rates of deforestation (Engel et al., 2008). Although the scale of payments made under most PES schemes is unlikely to provide sufficient incentive to initiate migration, PES payments may exacerbate already rapid in-migration. Additionally, in the absence of formal land title, land ownership records and an integrated land registry, the potential for gaming of PES payments systems is very high. Although we do not have empirical data from our study area on compliance with conservation programs, this sort of strategic behavior was common in one local PES effort where landholders received in-kind payments in exchange for agreeing not to clear new forest clearing. Landholders would abide by the agreement on one parcel of land while concealing additional landholdings where they cleared forest unabatedly, continuing to receive the payments for avoided deforestation. In the absence of land registration, most incentive-based schemes are likely to experience similar problems with gaming and enforcement. Lastly, as we have shown with in this paper, the opportunity cost of sparing forest increases rapidly through time on the frontier. Payment levels designed to be cost-effective at one stage of frontier development are likely to be insufficient at later stages of development.

5.3. Conclusion

In this paper, we have shown that land markets can arise rapidly after the first settlement of colonists in a new frontier area and can be very active, even in the absence of formal land title. Land markets in the three frontier districts in Peru showed consistent patterns of change through time: land sales reported from later years involved parcels that were smaller, had a lower proportion of forest, and were more expensive per hectare. By using a hedonic model of land price, we estimated by how much additional forest clearing would increase the price of land and showed how that increase changed through time. Although frontier areas in distinct stages of development showed different opportunity costs for forest sparing, the opportunity cost over time increased rapidly in all three areas-by US $124-$226 per hectare per year or 9–27% per year-during the decade of 2003–2013. Conservation initiatives must consider the dynamic nature of opportunity costs of forest clearing and sparing if they are to be effective. Indeed, in newly-settled frontier areas, policies focusing specifically on addressing land speculation may be more effective in stemming forest loss than incentive-based forest conservation approaches.

Acknowledgements

We gratefully acknowledge our informants in San Martin for their kind collaboration that made this project possible. Ronald Mori Pezo provided indispensable support in the field with interviewing, logistics, and community relationships. Cinthia Mongylardi, Braulio Andrade, and the staffs of CIMA and Conservation International in San Martin provided introductions to local officials and insight into conservation dynamics in our study areas. Our article benefited greatly from the thoughtful comments and suggestions of Gillian Gregory, Catherine Potvin, Jon Unruh, and two anonymous reviewers. Funding support was provided by the Social Science and Humanities Research Council of Canada (MSFSS 771–2012-0027) and Department of Geography, McGill University.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landusepol.2016.08.015.

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