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Converting Forests to Farms: The Economic Benefits of Clearing Forests in Agricultural Settlements in the Amazon

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Abstract Agricultural expansion into tropical forests is believed to bring local economic benefits at the expense of global environmental costs. The resulting tension is reflected in Brazilian government policy. The national agrarian reform program has settled farm families in the Amazon region since the 1970s, with the expectation that they will clear forests in order to farm the land. On the other hand, recent Brazilian policy initiatives seek to reduce deforestation to mitigate climate change. We contribute to the policy debate that surrounds these dual goals for the Amazon by estimating the marginal effects of new agricultural land on the full income and assets of farm settlers over a 13-year period from 1996 to 2009. Using micro panel data from agrarian settlements where forest was being rapidly cleared, and controlling for factors that would otherwise confound the relationship, we estimate the effect of converting forest to agriculture on total household income to estimate the opportunity cost of conserving forest. Our measure of income reflects any re-allocation of resources by utility maximizing households and any productivity effects due to loss of forest ecosystem services. The estimated effect of new agricultural land on income is positive, but small relative to the income per hectare of previously cleared land. However, we show that income increases

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investment in physical assets, which raises households' income generating capacity and future accumulation of assets. Thus, while there is only a small immediate income gain from clearing more forest, the long-term effects on wealth are still substantial. This demonstrates that given the right conditions, conversion of forest to agricultural land can be an impetus for asset accumulation by smallholders. It also highlights the importance of considering the indirect and long-term welfare benefits of new agricultural land when assessing the opportunity costs of forest conservation.

Keywords Brazil · Deforestation · Welfare · Agrarian settlement · Dynamic panel

1 Introduction

Global agricultural land area increased by more than 629 million ha in the 1980s and 1990s, the vast majority converted from forests, grasslands and other natural habitats in developing countries (Gibbs et al. 2010). A further 1 billion ha of agricultural conversion is forecast by 2050, which is predicted to lead to the loss of a third of remaining tropical and temperate forests, savannas and grasslands (Tilman et al. 2001). This presents serious threats to biodiversity, protected areas, and ecosystem services (Laurance et al. 2014; Tilman et al. 2011; Chomitz 2007). Agricultural expansion is fundamentally driven by rising demands for food, resulting from population and income growth (Laurance et al. 2014). However, national governments play an important role, either by passively allowing conversion of natural ecosystems or through policies that actively encourage new agricultural conversion.

Frontier settlement or colonization programs are one way that governments encourage conversion of native habitat to agriculture. During the 1980s and 1990s, small farmers participating in state-sponsored agrarian settlement programs across Latin America and Southeast Asia were a major driver of tropical deforestation (Rudel et al. 2009). Program objectives included populating remote regions as a geopolitical strategy, reducing rural unrest sparked by unequal land distribution in established agricultural regions, increasing agricultural production to meet market demands, and providing opportunities for rural and regional economic development (De Koninck and Déry 1997; Pacheco 2006; Manshard and Morgan 1988; Zoomers 1988). Agrarian settlement programs have been criticized on the grounds of high environmental costs and minimal economic benefits (Barbier 2004; Fearnside 1997; Delang 2002; Smith 1981). However, the Brazilian government has continued to settle farm families in the Amazon, making it pertinent to quantify the economic benefits of clearing forest in agricultural settlements.

Around 1.2 million families participated in the state-sponsored agrarian settlement program in Brazil between 1964 and 2006, mainly in the Legal Amazon (Pacheco 2009). INCRA (the National Institute of Colonization and Agrarian Reform) allocated properties to households with the expectation that they would farm the land, and thereby generate improvements in family welfare. These properties were initially forested, but no market existed to enable the sale of timber, so the main decision faced by households was the rate and extent to which they should fell and burn the forest biomass to create productive agricultural land. More than a fifth of all deforestation in the Brazilian Legal Amazon through 2013 occurred in INCRA settlements, which cover just 8% of the land area (Yanai et al. 2015). The economic benefits of these settlements have long been questioned (Goodland and Irwin 1975; Rodrigues et al. 2009; Murphy et al. 1997; Schneider et al. 2002). In particular, INCRA has been criticized for settling farmers on poor quality land and allowing them to be displaced to new frontiers

(Peres and Schneider 2012). The Brazilian government has sought to address these concerns, by identifying the most appropriate regions for agricultural development through zoning and clarifying land titles under the *Terra Legal* initiative. This still leaves the question of how much settler households benefit from clearing forest land when they have secure title to land that has the capacity to support agriculture.

This question has become more urgent as developing countries face increasing pressure to reduce conversion of natural ecosystems to agriculture under the Paris Climate Agreement (UNFCC 2015). At the same time the impacts of population growth, rising incomes and policies favoring bioenergy on global demand for agricultural output mean that governments in countries with unexploited land have strong incentives to encourage agricultural conversion. Given this tension between growing demands to preserve standing forest and continuing demands for agricultural land, we estimate the opportunity costs of foregoing new clearing in Brazilian agrarian settlements. Specifically, we examine the contribution of agricultural conversion to income and assets in several early agrarian settlements in the state of Rondônia where soils were relatively well-suited for agriculture and property rights were secure compared to settlements in other parts of the Amazon.

Prior efforts to understand the opportunity costs of avoided agricultural conversion have been constrained by data availability. Estimates based on the income earned from land used for cropping or ranching (e.g. Margulis 2004; Naidoo and Iwamura 2007; Börner and Wunder 2008; Bowman et al. 2012) provide important evidence on the immediate financial implications of reducing conversion, but do not capture the full welfare effect after behavioral adjustments such as re-allocation of resources by utility-maximizing households, loss of ecosystem services, and re-investment of income from new agricultural land in productive assets that raise future income generating capacity. These omitted factors could cause the opportunity cost to be over or under estimated. Other studies have examined the correlations between clearing forest land for agriculture and income/development across countries or census units (Barbier 2004; Margulis 2004; Rodrigues et al. 2009; Celentano et al. 2012; Caviglia-Harris et al. 2016). However, changes in aggregate measures of welfare may reflect migration rather than changes in the status of households, or reflect confounding factors that cannot be measured with census data.

We employ micro panel survey data linked to remote sensing data, from agrarian settlements in the western Brazilian Amazon, to estimate the effect of agricultural conversion on household income and assets in the short and long term. We model these relationships for a sample of settler households who remain on the properties they were allocated by INCRA, thus capturing the intended conditions in these settlements. Our unique dataset allows us to assess the role of forest clearing in the development of these agrarian settlements using more comprehensive measures of household welfare than are typical in the literature, and to study individual households over a long time horizon.

We extend the literature on the benefits of agricultural expansion for local actors in three ways. First, we estimate the contribution of cleared land to total income earned by household members living on the property, while controlling for unobserved household and land characteristics that may otherwise confound the relationship. Our measure of income reflects household optimization in response to agricultural conversion, such as shifting labor into or out of non-agricultural work, and incorporates any effects of property-level loss of forest ecosystem services on income. Second, we also estimate the contribution of cleared land to household wealth as measured by ownership of physical assets, a relatively stable indicator of welfare. Third, we estimate the indirect and long run impacts of agricultural expansion on income and wealth by accounting for investments in physical assets; the effects those assets

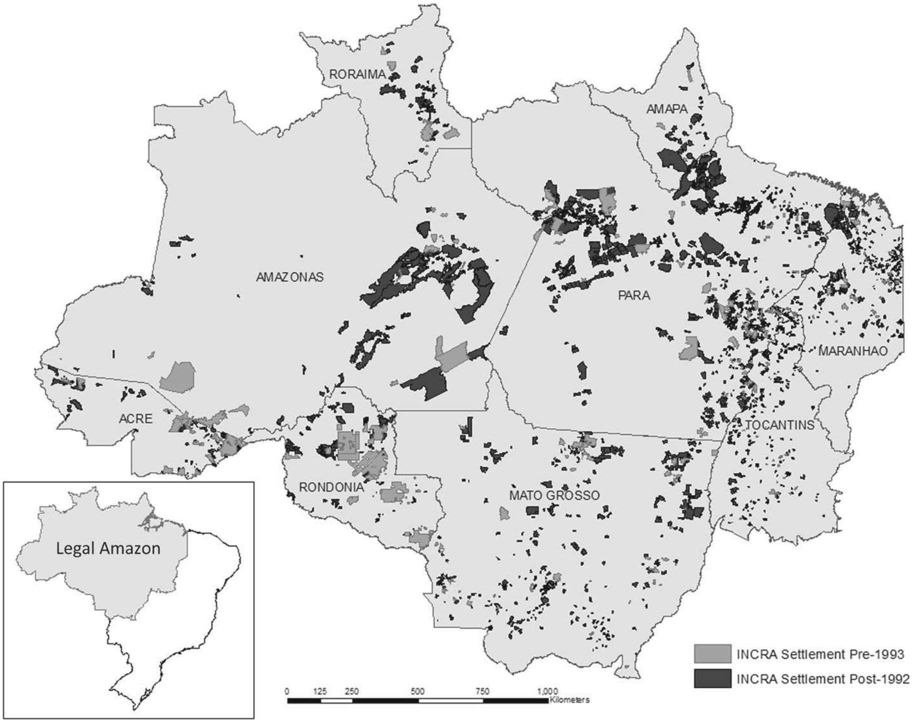

Fig. 1 Map of INCRA settlements within the Brazilian legal Amazon

have in turn on future income generating capacity; and any positive or negative feedbacks from income and wealth to further land use change.

2 Study Region

The Brazilian Amazon has the world's greatest stock of forest carbon, unmatched biodiversity (Malhi et al. 2008) and historically, some of the most rapid rates of deforestation (FAO 2010). Brazil also has one of the most significant frontier colonization programs to be administered in the past century, settling over one million individuals in the Amazon since 1970 with oversight by INCRA (Schneider and Peres 2015). Although these settlements cover only 8% of the more than 5 million square kilometers within the Legal Amazon (Fig. 1), 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 503 municipalities that intersect with INCRA settlements (out of the 757 municipalities in the Brazilian Legal Amazon that originally had at least 50% forest cover) accounted for 86% of deforestation up to 2010 in the Brazilian Legal Amazon.[1]

The population of the Brazilian Amazon grew by over 3% per year in the 1970s and 1980s, slowing to 2% per year by the 2000s (IBGE 2011). Initial in-migration followed roads constructed by the federal government to promote development (Barni et al. 2014).

[1] Based on authors' analysis of data from INCRA (2012) and INPE (2017).

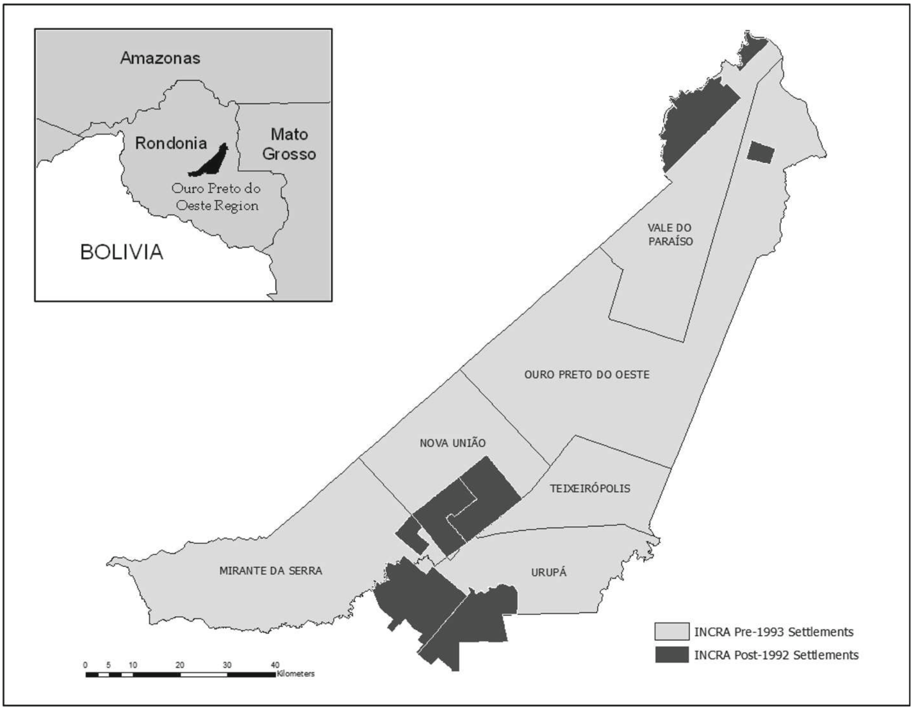

Fig. 2 Map of study region (post-1992 settlements excluded from sample)

Observers predicted that a cycle of land acquisition, deforestation, soil impoverishment and property abandonment would lead to a "hollow frontier" (Rudel et al. 2002). However, the farm failure and onward migration predicted by such turnover hypotheses has not been the dominant pattern in recent decades (Campari 2005; Caviglia-Harris et al. 2016). Rather, as the Amazon has urbanized (IBGE 2011), rural-urban migration of settlers and their children has become a more common trend (Caviglia-Harris et al. 2013; Macdonald and Winklerprins 2014; Ludewigs et al. 2009).

Our study site is an old or 'post' frontier region, having been first settled in the 1970s following construction of a controversial interstate road (BR-364) (Pedlowski et al. 1997). It consists of the six agrarian reform settlements that eventually became the six municipalities of the Ouro Preto do Oeste (OPO) region in central Rondônia, Brazil (Fig. 2). Although INCRA has created new settlements in these municipalities as recently as 2005, the six settlements in our study were all established at least 25 years ago. The land in this region is considered "good-average" for agricultural use, which is better than average for the Amazon.[2] In the six original settlements in Ouro Preto do Oeste, INCRA awarded formal titles to 100 (and later 50) hectare parcels along rectangular grids. The property boundaries were established without consideration for topography, hydrology, soil type or other environmental constraints

[2] Locations with different soil types are rated based on their ability to support agriculture: 1-good; 2-good-average; 3- average-good; 4- average; 5- average-restricted; 6-restricted; 7 restricted-unfavorable; 8-inadvisable. The average rating (across all pixels) for Ouro Preto do Oeste is 2.3, while the average for the Legal Amazon is 5.4. Source: IBGE (1992) "Mapa 1.19 Potencialidade Agricola dos Solos" from the *Atlas Nacional do Brasil;* data downloaded from http://www.mmnt.net/db/0/0/geoftp.ibge.gov.br/mapas_interativos, Accessed January 2015.

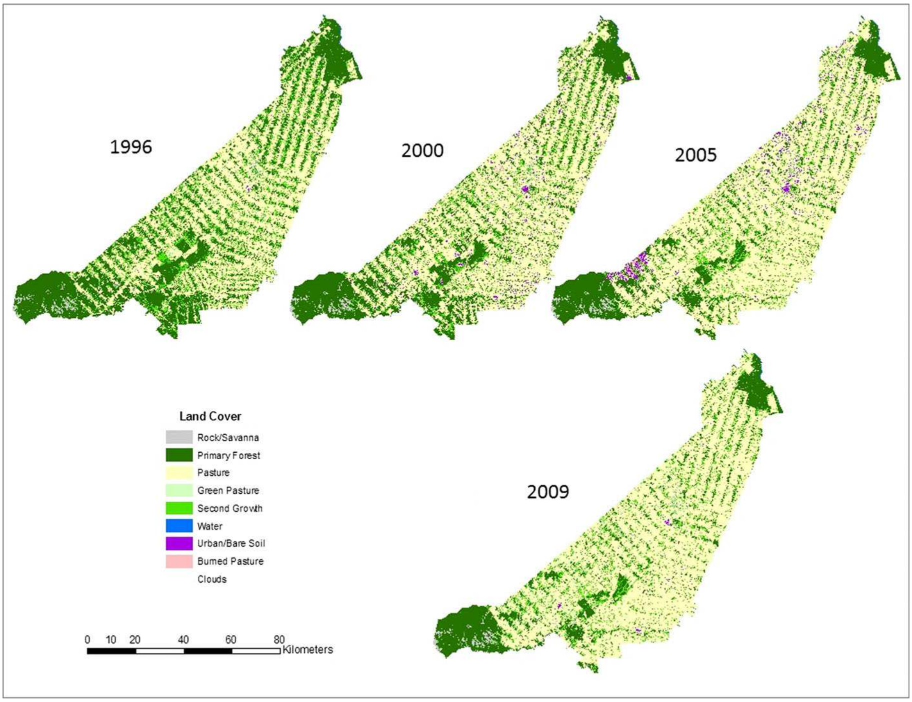

Fig. 3 Land cover in the study region in years corresponding to four waves of survey

(Millikan 1992), and have been gradually cleared in a 'fishbone' pattern typical of settlements in the Amazon (Fig. 3).

The Brazilian Forest Code (first established in 1934) declared that private forests throughout the nation were to be preserved to maintain hydrological services and geological stability. A complementary law passed in 1989 restricted deforestation to a maximum of 50% of any rural property, with the remaining 50% to be protected as a Legal Reserve (Brancalion et al. 2016). In 2001, deforestation was further restricted by federal law to a maximum of 20% of rural properties in the Amazon. Clearing of up to 50%, and later 20%, of the forest on a given property was therefore legal during most of our study time frame. Regardless, these laws have generally not been enforced in the Amazon and therefore have not effectively constrained deforestation in the study region, which was 81% deforested by 2015 (INPE 2017). A 2012 revision of the forest code offered amnesty for deforestation prior to July 2008 to smallholders, including landowners in the six agrarian reform settlements in our study site (Soares-Filho et al. 2014).

The municipalities of Ouro Preto do Oeste have similar settlement histories and patterns of land use to other municipalities in the Brazilian Amazon with INCRA settlements, particularly those established between 1970 and 1993, although there are some differences in the specific trajectories and drivers of economic growth (see Table 6 in the appendix). In Fig. 4, we compare the Human Development Index (a composite index of life expectancy, education, and income) and the income component of that index (derived from GDP per capita) across different categories of municipalities. The municipalities in Ouro Preto do Oeste initially had a lower HDI and income component than the averages for other municipalities with INCRA settlements, but subsequently grew relatively quickly. Thus, our study site appears to be a success story for agrarian settlement in the Amazon, with development proceeding hand in

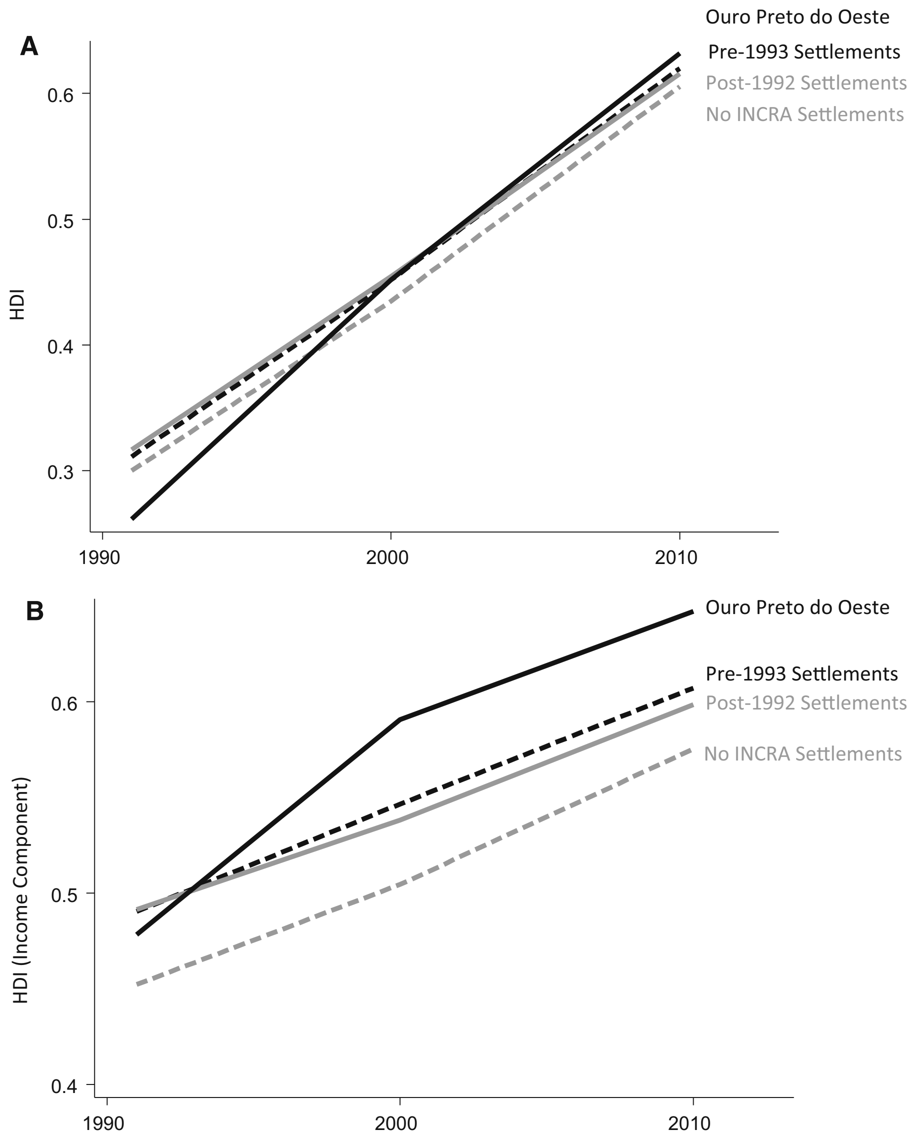

Fig. 4 Welfare comparison of study region and other municipalities in the Amazon: **a** Human Development Index (1991–2010) for (i) six municipalities in greater Ouro Preto do Oeste, (ii) other municipalities with settlements established pre-1993, (iii) municipalities with settlements established post-1992, and (iv) municipalities with no formal settlements (no INCRA settlements). **b** Income component of the Human Development Index (1991–2010). *Source*: PNUD. 2013. "Desenvolvimento Humano e IDH." Programa das Nações Unidas para o Desenvolvimento. http://www.pnud.org.br/IDH/DH.aspx Accessed Janaury, 2016.

hand with deforestation. However, these general trends do not necessarily reflect either the experience of individual settler households or the contribution of forest clearing to changes in welfare.

There are broad similarities in the underlying farm household production system in INCRA settlements across the Amazon, including Ouro Preto do Oeste. Settler households gradually clear the forest to grow annual (maize, rice, beans, and manioc) and perennial (cacao, coconut, and coffee) crops and increasingly raise cattle (Caviglia-Harris 2004). Due to limited markets for timber and prior harvest of the most valuable species (e.g. mahogany), settlers burn the trees to fertilize their land rather than selling them for timber. After an initial period of high soil fertility following land conversion, agricultural productivity falls unless the household applies sufficient mechanical, chemical and/or labor inputs (Davidson et al. 2007; De Camargo et al. 1999). Markets are fairly well integrated and complete for most agricultural outputs and some agricultural inputs. However, INCRA has generally not condoned or recognized sales of land in the settlements (Ludewigs et al. 2009), and the limited number of labor transactions, as well as the influence of household labor availability on production found in previous modeling, suggests that the labor market is very thin (Caviglia-Harris 2004). Difficulties accessing credit have also been found to limit small farmers' ability to invest in new economic activities (Vosti et al. 2001; Campari 2005). Thus, we employ theoretical and empirical approaches that are applicable to these incomplete market conditions.

3 The Model

The conceptual framework guiding this study is a dynamic version of the household production model. Households are consumers and producers of goods and maximize utility subject to technology and endowment constraints (Shively 2001; Sills et al. 2003). The rural economy is driven by household production of agricultural goods (q_a) and non-agricultural or off-farm goods and services (q_o) sold at market prices (p) that vary with distance to urban centers (d).[3] Income (Y) is equal to the sum of revenue from agricultural ($p_a q_a$) and non-agricultural ($p_o q_o$) production minus all purchased inputs ($p_x x$), and is a positive function of cleared land, labor and assets, conditioned on human capital, in particular education and local experience, E, and the biophysical characteristics of the property, in particular soil type and slope, B. Each household has a limited amount of labor $\bar{L}$, which is divided between agriculture (L_a), forest clearing (L_c), non-agricultural labor (L_o) and leisure (including household chores) (L_l). Households are also endowed with $\bar{H}$ hectares of land, originally all forested (H_f), and use labor to convert some each year to cropland or pasture (H_a). The productivity of agricultural land declines over time due to declining soil fertility and increases in pests and weeds such that $\partial q_{at}(\cdot)/\partial H_{ats} > \partial q_{at}(\cdot)/\partial H_{at(s+1)}$ where $t$is the current year, indexed from the year the property was first settled, and $s$is the number of years since the land was cleared. The accumulation of assets (A) depends on investment (I) and the rate of depreciation (γ). Recognizing that assets such as vehicles or telephones may be inputs to agricultural and non-agricultural activities and utility, we specify a single asset index.

Given these conditions, the household chooses labor allocations and the rate of investment to maximize discounted (β) utility (u) over an infinite time horizon that reflects concern for descendants, where utility is a function of consumption (c), leisure, and assets, conditional on the size of the household $\bar{L}$, and preferences as represented by E:

$$\text{Max} \sum_{t=1}^{\infty} \beta^{t-1} u_t \left(c_t, L_{lt}, A_t; \bar{L}, E \right) \tag{1a}$$

$$\text{st } Y_t = p_{at}(d)\, q_a \left(\sum_{s=1}^{s=t} H_{ats}, L_{at}, A_t; E, B \right) + p_{ot}(d)\, q_o \left(L_{ot}, A_t; E \right) - p_{xt}(d) x \tag{1b}$$

[3] Due to transportation costs and lack of integration into markets, both of which are proxied by distance, farmgate prices for outputs decline while farmgate prices for inputs rise with distance.

$$\bar{L} = L_{at} + L_{ot} + L_{ct} + L_{lt} \tag{1c}$$

$$\bar{H} = \sum\nolimits_{s=0}^{s=t} H_{ats} + H_{ft} \tag{1d}$$

$$H_{at} = g\left(L_{ct}\right) \tag{1e}$$

$$A_{t+1} = (1-\gamma)\, A_t + I_t \tag{1f}$$

$$c_t = Y_t - I_t \tag{1g}$$

We do not include markets for labor, land or credit as a simplified representation of the incomplete markets that are observed in practice in the study region. The implication of this assumption is that H_a and A evolve gradually because agricultural conversion is constrained by labor availability and the asset growth of credit constrained households is limited by income. Forest clearing may also be constrained by policy, although we do not make specific assumptions about this given the lack of enforcement during our study period.[4]

We represent the household maximization problem with the following Lagrangian:

$$\begin{aligned}\mathcal{L} = \sum\nolimits_{t=0}^{\infty} \beta^{t-1} \Big\{ & u_t\left(c_t, L_{lt}, A_t; \bar{L}, E\right) + \lambda_t \Big[p_{at}(d)\, q_a\left(\sum\nolimits_{s=1}^{s=t} H_{ats}, L_{at}, A_t; E, B\right) \\ & + p_{at}(d)\, q_o\left(L_{ot}, A_t; E\right) - p_{at}(d)\, x - c_t + (1-\gamma)\, A_t - A_{t+1} \Big] \\ & + \mu_t\left[g\left(L_{ct}\right) - H_{at}\right] + \nu_t\left[L_{at} + L_{ot} + L_{ct} + L_{lt} - \bar{L}\right] \\ & + \xi_t\left[\sum\nolimits_{s=0}^{s=t} H_{ats} + H_{ft} - \bar{H}\right]\Big\}\end{aligned} \tag{2}$$

The first order conditions with respect to consumption and asset accumulation show that households will invest in assets until the marginal utility from additional consumption in year t is equal to the discounted marginal utility from income and consumption in year t+1, given the net change in assets due to investment and depreciation and the returns to those assets (Eq. 3). Thus, investment varies with the marginal utility of consumption and assets; the discount rate; the prices faced by households; and the marginal productivity of assets in agricultural and non-agricultural production. Income affects investment through the marginal utility of consumption. This creates a channel for cleared land to affect asset accumulation indirectly through income. In addition, the marginal productivity of assets in agricultural production may vary with the area of cleared land, creating a potential second channel for land clearing to directly affect assets. In our empirical model, we test for both direct and indirect effects of agricultural conversion on assets.

$$\begin{aligned}& \beta^{t-1} \frac{\partial u\left(c_t, L_{lt}, A_t; \bar{L}, E\right)}{\partial c_t} \\ & = \beta^t \left\{ \lambda_{t+1} \left[p_{at+1}(d) \frac{\partial q_{at+1}\left(\sum_{s=1}^{s=t+1} H_{a(t+1)s}, L_{at+1}, A_{t+1}; E, B\right)}{\partial A_{t+1}} \right.\right. \\ & \left.\left. + p_{at+1}(d) \frac{\partial q_{ot+1}\left(L_{ot+1}, A_{t+1}; E\right)}{\partial A_{t+1}} + (1-\gamma) \right] + \frac{\partial u\left(c_{t+1}, L_{lt+1}, A_{t+1}; \bar{L}, E\right)}{\partial A_{t+1}} \right\}\end{aligned} \tag{3}$$

[4] The area of forested land would enter the farm and non-farm production functions if forest products or local ecosystem services were significant influences on household income. We do not include these in the theoretical model as our survey responses do not suggest that they are important at the individual household level. However, if these influences are present, they are captured in our empirical model, by the effect of agricultural area, controlling for property size, on total income (because the area of forest is equal to total property size minus agricultural area).

Households will allocate labor to clearing forest land until the marginal returns to labor in clearing are equal to the marginal returns to labor in agricultural and non-agricultural activities and leisure (Eq. 4).

$$\mu_t \frac{\partial g(L_{ct})}{\partial L_{ct}} = \lambda_t \left(p_{at}(d) \frac{\partial q_{at}\left(\sum_{s=1}^{s=t} H_{ats}, L_{at}, A_t; E, B\right)}{\partial L_{at}} \right) = \lambda_t \left(p_{at}(d) \frac{\partial q_{ot}(L_{ot}, A_t; E)}{\partial L_{ot}} \right) = \beta^{t-1} \frac{\partial u\left(c_t, L_{lt}, A_t; \bar{L}, E\right)}{\partial L_{lt}} \quad (4)$$

Better human capital (E) and property characteristics (B) imply higher returns to cleared land, labor and assets in agricultural production. All else equal, households with greater human capital will also receive higher returns to labor and assets in non-agricultural production. Prices for agricultural and non-agricultural outputs decline with distance from urban centers. As such, less remote properties will also have higher returns to cleared land, labor and assets. Assuming concave functions for agricultural and non-agricultural output, cleared land, and utility, higher values for these conditioning variables will therefore increase investment in physical assets, all else constant, by raising the returns to that investment relative to the utility from current consumption. The effects on forest clearing of higher levels of human capital, better property characteristics, and a more accessible location are ambiguous. They raise the relative returns to labor in agricultural and non-agricultural production, which would reduce labor allocated to clearing. However, they also raise the returns to cleared land in agriculture, which is expected to increase clearing. Household size and human capital also condition the effects of consumption, leisure and assets on utility. These factors may therefore alter the tradeoffs between current and future consumption, as determined by investment in physical assets or use of labor for clearing forest land.

4 Econometric Specification

We estimate household income (Y), household assets (A), and cleared hectares (H_a) as functions of the variables suggested by the theoretical model. Each of these variables is a function of the other two, as well as its own lagged value and a suite of mediating variables. Thus, in its most general form, the empirical model is as follows:

$$\mathrm{Y}_{it} = f(Y_{i,t-1}, H_{ait}, \mathrm{A}_{it}, X_{it}, \varepsilon_{it}; \beta_{\mathrm{Y}}) \quad (5a)$$

$$A_{it} = f(A_{i,t-1}, H_{ait}, \mathrm{Y}_{it}, X_{it}, \varepsilon_{it}; \beta_A) \quad (5b)$$

$$H_{ait} = h\left(H_{ai,t-1}, A_{it}, Y_{it}, X_{it}, \varepsilon_{it}; \beta_D\right) \quad (5c)$$

where i refers to households and t to time periods (years); the ß's are vectors of parameters to be estimated; and X includes exogenous factors, namely household (E) and biophysical (B) characteristics, market access (d), and the number of years since clearing of the property began (a proxy for the average vintage of the cleared land), all of which condition returns to cleared land and investment in assets (Eq. 1). These potentially include factors that can be influenced by households e.g. by attending training sessions, investing in soil improvements, or lobbying for public services, but we assume that these influences operate on longer time scales than observed in our dataset and therefore treat these factors as exogenous. We do not include weather shocks, environmental regulation or market prices for inputs and outputs in our econometric specification as these are covariant across the study region.

Estimating the system of Eqs. 5a–c allows us to model dynamic feedbacks between the key variables, for example the effects of assets on the income generating capacity of the household. However, there are a number of challenges associated with econometric estimation of this model. First, unobserved heterogeneity across households may influence the observed outcomes. Second, the key variables, in particular wealth and area of cleared land, are cumulative and therefore are functions of lagged values of themselves as well as other variables. Third, clearing forest for agriculture may be simultaneous or otherwise endogenous to income due to the household time constraint, just as income and wealth are simultaneously determined due to the lack of credit.

To address the first challenge, we use first-differenced panel data to control for unobserved heterogeneity by eliminating time-invariant unobserved differences in the characteristics of the property, and the innate abilities, beliefs or motivations of the households. First-differencing introduces negative correlation between the differenced lagged dependent variable—introduced to address the second challenge—and the differenced disturbance term (see Bond 2002).[5] We therefore use second-order lagged values of the dependent variable as instruments for the differenced lagged dependent variable, and second-order lagged differences as instruments for the lagged dependent variable in levels, to address endogeneity. This 'System-GMM' model[6] is an extension of Arellano and Bond's (1991) 'Difference-GMM' model,[7] and offers efficiency gains in short panels (Arellano and Bover 1995; Blundell and Bond 1998).

As well as instrumenting the lagged dependent variable with further lags to address the problem of dynamic panel bias, we use lagged observations in a similar manner to instrument the endogenous explanatory variables, to address the third econometric challenge. This requires that lagged values of the dependent and endogenous variables are not correlated with the first-differenced error term, and similarly, that lagged differences are not correlated with the error term in levels. These are significant assumptions, which we test using the Hansen J test for overidentifying restrictions and the difference-in-Hansen test of the exogeneity of subsets of instruments (Baum et al. 2003; Roodman 2009). As reported in the results section, these indicate that in each of the models estimated, the instruments are jointly exogenous. These tests also suggest a better fit for the System-GMM model than the Difference-GMM model.[8]

5 This correlation becomes negligible as the number of time periods becomes large but is considerable with a short panel such as the one we are using.

6 We use two-step estimation with the Windmeijer correction for calculation of the standard errors and with the full set of available lags. The model is estimated in Stata using the xtabond2 command (Roodman 2009).

7 The Difference-GMM model is estimated only in first-differences, using second order lagged values of the dependent variable as instruments for the differenced lagged dependent variable. The System-GMM model is estimated in both first-differences and levels.

8 The other condition for using these 'GMM-style' instruments is that they have some predictive power for the variables that they are being used to instrument. The problem of weak instruments in generating inconsistent estimates and biased parameters in finite samples has been widely recognized (see e.g. Bound et al. 1995). As GMM simultaneously estimates the full system of equations, we cannot directly observe the 'first stage' model and thus must simply assume that our instruments have predictive power (Stock et al. 2002). The other explanatory variables in the model are assumed to be strictly exogenous.

5 Data

The data used in the empirical analysis come from a sample of 106 households in the six municipalities of Ouro Preto do Oeste. These households were interviewed in 1996, 2000, 2005 and 2009, with all interviews conducted face-to-face by trained interviewers and only 1–2 refusals in each survey wave. These survey data are combined with remote sensing data (derived from 30 m resolution LandSat Enhanced Thematic Mapper images) on land cover in each survey year. The LandSat images were classified using decision tree classifiers and spectral mixture analysis, as described by Roberts et al. (2002). Accuracy, assessed using Google Earth imagery, was 90.5% overall, exceeding 80% for all classes. Property boundaries are taken from INCRA's cadastral maps. Distance to market is calculated using GPS data on surveyed properties, road networks, and urban commercial centers. Details of the field methods and tests of the reliability and representativeness of the data are reported in Caviglia-Harris et al. (2009, 2012, 2013) and Caviglia-Harris and Harris (2005, 2008).

Our sample is comprised of the households who remained on their properties throughout the study period (1996–2009). In 1996, 166 households were drawn in a random sample, stratified by the six INCRA settlements, and 25 households who participated in a local agricultural association were included in an additional purposive sample (Caviglia 1999). More than half (106) of those 191 households remained on the same properties at least until 2009. This "stable panel" allows us to examine how converting forested to agricultural land affects welfare when agrarian settlement unfolds as intended by INCRA, with settlers staying on properties with soils appropriate for agriculture and uncontested tenure. Compared to the 85 farm households that moved (or dissolved) between 1996 and 2009,[9] the average household in our sample had slightly less education and more family members, but had similar levels of income, assets, and cleared land in 1996 (Table 1).

5.1 Outcome Variables

Average annual household income in our sample grew from approximately R$7,000 in 1996 to R$24,000 in 2009, representing an increase in real terms of about 9% per year (Table 2). We calculate income as short-run earnings, or "value added" to the household endowment of labor and land (cf. Pattanayak and Butry 2005). This measure of economic welfare, previously used in Shone and Caviglia-Harris (2006), Caviglia-Harris et al. (2013), is the total value of agricultural production ($p_a q_a$) plus non-agricultural earnings and government payments ($p_o q_o$).[10] This measure captures the full value of all production and income earned from the property, thus incorporating multiple possible influences of deforestation, including both creating new land for agricultural production, and changing ecosystem services from forest on the property itself (e.g. shade for cattle, sediment load in streams used for aqua-

9 High rates of turnover in agrarian reform settlements have been implicated in the rapid advance of the deforestation frontier in the Brazilian Amazon (Fearnside 2008). Of the 85 full households who moved off their lots in our study settlements, 67% moved for reasons that can be classed as life improvements or pull factors (e.g. work, study, new home purchase), while 18% moved for negative reasons, or push factors (e.g. poor health or inability to support their family on the farm), and 16% moved for family reasons such as marriage or divorce (Caviglia-Harris et al. 2013). Of those who moved, 72% stayed within the study region or adjacent municipalities, often moving to urban centers, while 15% moved out of the Amazon. Thus, at most 13% of our sample moved to new frontiers within the Amazon (see Caviglia-Harris et al. (2013) for more details).

10 Non-agricultural earnings come primarily from employment and family businesses, but also include forest product sales, rental receipts, remittances, and government payments (e.g., pensions and cash transfers such as Bolsa Familia).

Table 1 Comparison of stable panel and households that moved (Mean values in 1996)

	Households in stable panel	Households that moved to a new property after 1996	Difference	t-statistic
Total income (R$ 2000)	7147.84	7594.32	446.48	0.35
Principal Comp. of Assets	−1.38	−1.60	−0.23	−1.33
Area of cleared land (ha)	54.63	56.04	1.41	0.36
Area of lot (ha)	78.15	77.22	−0.92	−0.21
Travel time to city (mins)	67.30	67.55	0.24	0.05
Mean slope (degrees)	5.54	4.90	−0.64	−1.23
Soil (8-point scale, 1=suitable for ag)	2.17	2.34	0.17	1.52
Years since first cleared	19.47	19.48	0.01	0.01
Year male head arrived in Rondônia	1978	1979	1.35	1.65
Av. education of HH heads (years)	2.33	2.98	0.65*	1.78
Av. age of HH heads (years)	46.39	43.34	−3.05	−1.61
Origin of male head (1=S or SE Brazil)	0.80	0.82	0.02	0.38
Family size	9.55	7.42	−2.12***	−2.62
N	106	85	191	

$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

culture, availability of forest products), including when those influences occur with a time lag. We measure income as collectively earned and reported by the household, rather than transforming to a per capita measure, and hence all of the multivariate models include controls for household size. The theoretical effect of household size on wealth and land clearing is unknown based on our model, as a larger household has more available labor (potentially increasing either outcome), but also greater consumption needs (reducing household willingness to trade off current income for future income). Specifically, we model the natural log of income. All values are reported in the Brazilian currency (R$ or reais) and adjusted for inflation to the year 2000 (when R$2 was approximately equivalent to US$1).

Our second measure of welfare is the stock of physical assets owned by the household. To combine diverse assets into a single index, we follow the approach of Kolenikov and Angeles (2009), weighting the contribution of different asset types to a wealth index using polychoric Principal Component Analysis (PCA). The assets included in the index are key consumer and producer durables (chainsaw, television, satellite dish, telephone, and refrigerator); vehicles owned by the household (bicycle, motorcycle, car, truck and tractor); the number of urban houses owned; the area of land owned (in addition to the primary property); and the number of cattle owned. Similar to household income, physical wealth has been increasing over time, as represented by the increase in the first principal component from an average of -1.36 in 1996 to 1.15 in 2009 (Table 2). We compare the main results with estimation results for specifications using an alternative measure of assets that excludes cattle from the principal component. The size of the cattle herd could be considered mechanistically linked to deforestation since cattle require cleared land for pasture, potentially resulting in an overestimation of the relationship between agricultural expansion and wealth.

The third outcome variable is the area of cleared land. A land cover accuracy assessment resulted in a high level of confidence in distinguishing mature forest cover from the other land cover classes in our LandSat image classification (see Roberts et al. (2002) and Fig. 3).

Table 2 Descriptive statistics for outcome and explanatory variables

	1996	2000	2005	2009
Total income (R$ 2000)	7147.8	15194.4	15050.8	24366.9
	(6367.0)	(13896.8)	(12066.4)	(66164.6)
Principal Comp. of Assets	−1.376	−0.237	0.523	1.146
	(1.344)	(1.538)	(1.541)	(1.543)
Area of cleared land (ha)	54.63	63.02	67.76	69.72
	(26.89)	(29.84)	(34.60)	(34.47)
Area of lot (ha)	78.15	79.04	81.21	80.26
	(31.08)	(32.93)	(37.43)	(37.60)
Travel time to city (mins)	67.30	67.31	57.65	57.65
	(32.23)	(32.04)	(27.77)	(27.77)
Mean slope (degrees)	5.543	5.539	5.561	5.549
	(3.578)	(3.577)	(3.571)	(3.590)
Soil (8-point scale, 1=suitable for ag)	2.172	2.170	2.172	2.172
	(0.797)	(0.799)	(0.804)	(0.804)
Years since first cleared	19.47	23.47	28.47	32.47
	(8.747)	(8.747)	(8.747)	(8.747)
Year male head arrived in Rondônia	1978.1	1979.1	1979.1	1979.0
	(5.915)	(6.046)	(6.237)	(6.297)
Av. education of HH heads (years)	2.330	2.575	2.637	3.344
	(2.177)	(1.590)	(2.088)	(2.939)
Av. age of HH heads (years)	46.39	47.58	54.20	55.96
	(12.49)	(12.05)	(11.00)	(13.66)
Origin of male head (1=S or SE Brazil)	0.802	0.802	0.802	0.802
	(0.400)	(0.400)	(0.400)	(0.400)
Family size	9.547	8.123	6.642	5.764
	(6.582)	(5.944)	(3.525)	(3.650)
N	106	106	106	106

Means are reported, with sd in parentheses

Thus, as practically all the land in this region was initially forested, we calculate the area of land cleared as the size of the property minus the area currently in mature forest. The cleared area has steadily increased over the study period from 55ha in 1996 to around 70ha by 2009, implying an annual rate of loss of mature forest of approximately 4.3% (Table 2). We use the natural log of total area cleared ($\ln(H_a)$), and include a control for the total size of the property. The theoretical model assumes that the productivity of cleared land declines with age (i.e. with time since deforested, or s). To proxy for average age of the cleared land, we include the number of years since deforestation of the property began (almost 20 years on average as of 1996).

5.1.1 Conditioning Variables

We include three categories of conditioning variables in the empirical models to account for factors that influence the returns to cleared land and physical assets. They also affect the marginal productivity of labor in different uses, and therefore decisions about labor allocation and investment. These categories are market access (d in the theoretical model), human capital (E), and biophysical characteristics (B) of the property.

In the theoretical model, farmgate prices are a function of distance to urban center (representing transportation costs and market integration). We measure this as the travel time to the main town, which fell from 67 to 57 min between 1996 and 2009 on average due to road improvements (Table 2).

We represent current human capital with the average age of the male and female household heads and the year the household migrated to Rondônia, along with two measures of prior human capital: the average education of male and female household heads, and the region of origin of the household. By definition, the year of migration and state of origin have not changed over the survey timeframe, but education level (and age) have evolved to a limited extent as second generation settlers have taken over as household heads (Table 2). The year of migration serves as an indicator of experience with local conditions, while origin is a more general indicator of human capital, including health and quality of education. As compared to the Center and Northeast, the South and Southeast of Brazil have higher life expectancy and literacy rates (IBGE 2011), indicating better health and education systems that result in higher human capital among their emigrants.

Biophysical characteristics in the models include the property size, which increases slightly from 78 to 80 hectares over time due to a minority of families acquiring small additional pieces of land; the average slope gradient on the property, which averaged 5.5 degrees; and suitability of the soils for agriculture, which averaged 2.7 on an 8-point scale (Table 2). We treat these characteristics of the property as exogenous because most of the households in our 1996 sample were living on land that they had been assigned by INCRA upon their arrival in Rondônia, and our sample only includes households that remained on those same properties throughout the study period. We confirm that these assignments were not related to the origin or education of the settlers by regressing the characteristics of the properties on the characteristics of households in 1996 (Table 3). While agricultural suitability does not vary systematically with household characteristics, we do find that older household heads have larger properties that are nearer to the main urban center. This most likely reflects differences in time of arrival in the region and therefore we control for the year the household arrived in Rondônia in our models.

6 Results

The estimation results for the System-GMM models of household income (Y), assets (A) and hectares cleared (H_a) as functions of lagged values of themselves, each other, and exogenous property and household characteristics are presented in Table 4. For comparison, we also include estimation results from pooled OLS models with household clustered standard errors and from fixed-effects models with robust standard errors. Compared to the System-GMM model, the coefficient on the lagged dependent variable is known to be upwardly biased by OLS estimation and downwardly biased by fixed-effects estimation (Bond 2002). Consistent with this, we find that the coefficients on lagged income, assets and cleared hectares in the System-GMM models lie between the OLS and fixed effects coefficients. The Hansen tests of overidentifying restrictions (p values reported in Table 4) indicate that the instruments are jointly exogenous in each of the System-GMM models. We also report the p values for the Difference-in-Hansen tests for the exogeneity of the subset of the lagged instruments for the

Table 3 Results of regression of lot characteristics on pre-sample characteristics (all data from 1996)

	(1) Slope	(2) Soil suitability	(3) Lot size	(4) Distance to OPO
Av. education of HH heads (years)	−0.158	0.0194	0.502	−0.0783
	(0.120)	(0.0258)	(0.997)	(1.007)
Av. age of HH heads (years)	−0.00758	0.00138	0.356*	−0.526***
	(0.0236)	(0.00506)	(0.196)	(0.198)
South	1.869	−0.0732	−0.0578	7.458
	(2.646)	(0.567)	(21.94)	(22.15)
Southeast	2.259	−0.327	14.33	−7.925
	(2.595)	(0.556)	(21.52)	(21.73)
North	0.0485	−0.0701	−13.32	9.432
	(3.126)	(0.670)	(25.93)	(26.18)
Northeast	1.360	−0.219	0.0523	4.907
	(2.662)	(0.570)	(22.08)	(22.29)
Constant	4.019	2.398***	51.06**	94.61***
	(2.701)	(0.579)	(22.41)	(22.62)
Observations	191	191	191	191
R^2	0.027	0.013	0.058	0.108

Standard errors in parentheses
$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

three outcome variables in the levels equation. These subsets of the full instrument set also appear to be exogenous.

We first examine the determinants of household income (Eq. 5a). As we would expect, cleared land significantly increases household income. Based on the coefficients in Table 4, column 3, a 10% increase in cleared area leads to a 5.6% increase in household income. This confirms that forest clearing is important to short term welfare, and reflects the fact that households in our sample earn most of their income by raising cattle for milk and beef, which in turn requires the conversion of forest land to pasture. In practical terms, if the 2009 mean cleared area had been 10% less than it actually was, i.e. 63ha rather than 70ha, household income would have been R$1,290 lower. The implied opportunity cost of avoided forest clearing is therefore R$185/ha/year, which equates to around US$135/ha/year in 2016 prices. The theoretical model (Eq. 1b) suggests that another key determinant of income is the physical assets owned by the household, as these influence both agricultural and non-agricultural production. We confirm that the first principal component of assets is a significant determinant of household income. Once we control for cleared land and wealth, neither lagged income nor any of the other household and land characteristics directly affect current income.

The model in Sect. 3 suggests that agricultural expansion may directly affect decisions about accumulation of assets if clearing more land raises the returns to physical assets in the agricultural production function. Clearing may also indirectly affect investment in assets by increasing income. We test both of these relationships with our empirical model. We do not find evidence of a direct impact of cleared area on assets: conditional on income, the area of cleared land is not associated with significantly higher or lower levels of wealth.

We do find evidence that agricultural expansion indirectly affects wealth through the mechanism of higher household income. Income has a positive, significant effect on wealth,

Table 4 Main estimation results

	(1) Ln(Inc)-OLS	(2) Ln(Inc)-FE	(3) Ln(Inc)-SGMM	(4) Assets-OLS	(5) Assets-FE	(6) Assets-SGMM	(7) Ln(Clear)-OLS	(8) Ln(Clear)-FE	(9) Ln(Clear)-SGMM
Ln(Income)				0.405***	0.323***	0.286***	0.000474	0.0365	0.0118
				(0.0788)	(0.0736)	(0.0911)	(0.0205)	(0.0221)	(0.0186)
Ln(Income)$_{t-1}$	0.212***	−0.307***	−0.0235						
	(0.0682)	(0.0725)	(0.101)						
Ln(Cleared area)	0.0146	0.695***	0.563*	−0.130	0.0206	0.306			
	(0.225)	(0.168)	(0.312)	(0.170)	(0.352)	(0.644)			
Ln(Cleared area)$_{t-1}$							0.681***	0.111	0.552***
							(0.0389)	(0.103)	(0.0745)
Asset index	0.215***	0.192***	0.184***				−0.00158	0.000189	−0.00344
	(0.0339)	(0.0412)	(0.0445)				(0.00615)	(0.00927)	(0.00759)
Asset index$_{t-1}$				0.504***	−0.120*	0.379***			
				(0.0629)	(0.0635)	(0.102)			
Lot size	0.00304	−0.00431*	−0.00206	0.00207	−0.00589	−0.00173	0.00576***	0.00817***	0.00779***
	(0.00291)	(0.00219)	(0.00389)	(0.00259)	(0.00425)	(0.00931)	(0.000683)	(0.00219)	(0.00111)
Time to city	0.00478**	0.00601	0.00257	−0.00680**	−0.0180	−0.00809**	0.000344	−0.00319	0.0000989
	(0.00234)	(0.00915)	(0.00252)	(0.00277)	(0.0148)	(0.00376)	(0.000331)	(0.00232)	(0.000490)
Years since cleared	0.00372		−0.00229	0.0102		0.0118	−0.00363*		−0.00151
	(0.00890)		(0.0113)	(0.0114)		(0.0169)	(0.00212)		(0.00282)

Table 4 continued

	(1) Ln(Inc)-OLS	(2) Ln(Inc)-FE	(3) Ln(Inc)-SGMM	(4) Assets-OLS	(5) Assets-FE	(6) Assets-SGMM	(7) Ln(Clear)-OLS	(8) Ln(Clear)-FE	(9) Ln(Clear)-SGMM
Slope	0.00210	−0.350	0.00742	−0.0372*	−0.0995	−0.0227	−0.00634**	0.0980	−0.00462
	(0.0113)	(0.399)	(0.0150)	(0.0201)	(0.494)	(0.0253)	(0.00273)	(0.0990)	(0.00283)
Soil suitability	−0.140**		−0.0852	0.0789		0.106	−0.0217		−0.0123
	(0.0678)		(0.0814)	(0.118)		(0.170)	(0.0171)		(0.0161)
Year arrived in Rondônia	0.00246	0.000684	−0.00160	−0.00723	0.00477	−0.00644	0.00152	−0.00155	0.000647
	(0.00589)	(0.00742)	(0.00700)	(0.00975)	(0.0136)	(0.0162)	(0.00129)	(0.00232)	(0.00109)
Age	0.00406	0.00342	0.00113	0.00200	0.00921	0.00367	0.000875	−0.000508	−0.000365
	(0.00400)	(0.00622)	(0.00533)	(0.00505)	(0.00830)	(0.00689)	(0.000849)	(0.000851)	(0.000864)
Education	0.0107	0.0264	0.0182	0.0195	0.0431	0.00118	−0.00512	−0.00654	−0.00522
	(0.0318)	(0.0365)	(0.0284)	(0.0295)	(0.0343)	(0.0440)	(0.00490)	(0.00493)	(0.00548)
South/Southeast	0.209*		0.110	−0.194		−0.267	−0.0208		−0.00449
	(0.109)		(0.143)	(0.134)		(0.168)	(0.0253)		(0.0343)
Family size	−0.0124	−0.00729	−0.0135	0.0728***	0.0655***	0.0791***	0.000205	−0.00118	0.000507
	(0.00920)	(0.00943)	(0.0104)	(0.0154)	(0.0185)	(0.0266)	(0.00172)	(0.00142)	(0.00162)
2005	−0.323**	0.139	−0.150	0.155	0.760***	0.207	−0.0414	−0.00348	−0.00842
	(0.124)	(0.140)	(0.148)	(0.184)	(0.213)	(0.227)	(0.0258)	(0.0260)	(0.0183)
2009	−0.263**	0.210	−0.0265	0.311	1.402***	0.495*	−0.0221	0.0341	−0.00370
	(0.132)	(0.187)	(0.171)	(0.196)	(0.258)	(0.250)	(0.0227)	(0.0224)	(0.0284)
Observations	318	318	318	318	318	318	318	318	318
Adjusted R^2	0.306	0.201		0.582	0.439		0.908	0.362	
Hansen p value			0.630			0.103			0.316
Diff-in-Hansen			0.663			0.131			0.651

Standard errors in parentheses, $^{*} p < 0.1$, $^{**} p < 0.05$, $^{***} p < 0.01$;
Model estimation methods: *OLS* Ordinary Least Squares, *FE* Fixed Effects, *SGMM* System Generalized Method of Moments

meaning that those with more cleared land will have more assets on average as cleared land increases household income, which increases wealth. The coefficient on income in Table 4, column 6 shows that a 1% increase in income is associated with a 0.29 point increase in the asset index. Further, the elasticity of income with respect to cleared land is approximately 0.56 (given by the coefficient on cleared area in the income model in Table 4, column 3). Multiplying the effect of cleared land on income by the effect of income on assets, this implies that a 10% increase in cleared area will increase the asset index by 1.62 points.[11] The standard deviation for the asset index across all time periods is 1.76, and for cleared land is 32ha. Therefore a 10% increase in cleared area, which is equivalent to 0.2 standard deviations, increases assets by 0.92 standard deviations, suggesting a substantial effect of agricultural expansion on household wealth.

The results described so far represent the impacts of cleared land on wealth in a single time period. However, the positive, significant coefficient on the lagged dependent variable in the asset model (Table 4, column 6) indicates that there is path dependence in household wealth, i.e. prior assets are a key determinant of current assets. This implies a dynamic feedback that magnifies the effect of agricultural expansion on wealth in the long run. Incorporating the asset dynamics (i.e. the effect of the lagged dependent variable), the total impact of a 1% increase in income is to raise the asset index by 0.46 points.[12] Using the same calculations as in the previous paragraph, this suggests that a 10% increase in cleared area (0.2 standard deviations) increases the physical asset index by 2.6 points (1.5 standard deviations) in the long run, a considerably larger effect than we observed in the short run.

A number of other characteristics of the household and property also affect wealth levels. Larger families tend to own more assets. Whether this translates to higher welfare depends on the extent to which the assets in question are rival in use, or whether larger households benefit from joint use of assets (e.g., radios and vehicles). Most other conditioning variables, including household characteristics that proxy for human capital, and the biophysical characteristics of the property, do not influence wealth. An exception is that households with properties further from the main urban center have fewer assets on average. Drawing on the theoretical model, this suggests that market access may be an important determinant of returns to physical assets, leading households with better access to invest more, conditional on income.

Our last set of results (Table 4, column 9) show the determinants of agricultural expansion (Eq. 5c). We find the main determinant of current cleared area to be past cleared area, which is expected given the cumulative and contagious nature of deforestation (Rosa et al. 2013). Controlling for past cleared area, we find–also not surprisingly–that households with larger properties clear more forest. The total labor force, as represented by the size of the household, is not a significant determinant of cleared area, which is surprising as labor availability was predicted to be the primary constraint on land clearing. However, household size also reflects consumption needs for the household, which affect the trade-off made between using labor for clearing forest (and therefore generating future income) and using labor to generate current income. These two different effects of household size may net out to zero. A limited local labor market, even if imperfect, could also reduce any positive relationship between household size and land clearing. The predicted direction of the impacts of the conditioning variables–market access, human capital and biophysical characteristics–was ambiguous. In

[11] This is calculated as: elasticity of income with respect to cleared land * impact of income on asset index * percentage change in cleared land i.e. 0.56*0.29*10.

[12] The total, or long-run, effect can be obtained using the formula for the infinite sum of a geometric sequence: $\sum_{n=0}^{n=\infty} \beta_{asset(t-1)}^{n} \beta_{income} = \frac{\beta_{income}}{(1-\beta_{asset(t-1)})}$.

Table 5 Alternative specifications

	Cattle excluded from assets			APA households excluded from sample			Farm income only		
	(1) Ln (Income)	(2) Assets	(3) Ln (Cleared)	(4) Ln (Income)	(5) Assets	(6) Ln (Cleared)	(7) Ln (Income)	(8) Assets	(9) Ln (Cleared)
Ln(Income)		0.201**	0.0117		0.301**	0.0172		0.146**	0.00194
		(0.0890)	(0.0183)		(0.121)	(0.0259)		(0.0561)	(0.00895)
Ln(Income)$_{t-1}$	0.00514			0.0207			0.148		
	(0.106)			(0.107)			(0.102)		
Ln(Cleared area)	0.578*	0.337		0.654**	0.641		1.685**	0.166	
	(0.331)	(0.682)		(0.272)	(0.699)		(0.819)	(0.608)	
Ln(Cleared area)$_{t-1}$			0.554***			0.513***			0.591***
			(0.0740)			(0.0731)			(0.0493)
Asset index	0.152***		−0.00452	0.178***		−0.000305	0.297***		−0.00432
	(0.0446)		(0.00788)	(0.0466)		(0.00999)	(0.0969)		(0.00886)
Asset index$_{t-1}$		0.400***			0.381***			0.380***	
		(0.112)			(0.110)			(0.118)	
Lot size	−0.00176	−0.00175	0.00781***	−0.00482	−0.00800	0.00864***	−0.0169	−0.000853	0.00767***
	(0.00410)	(0.00989)	(0.00111)	(0.00341)	(0.0112)	(0.00114)	(0.0120)	(0.00823)	(0.00101)
Time to city	0.00231	−0.00782*	0.000102	0.00277	−0.00776*	0.000320	0.00831	−0.0105**	0.000164
	(0.00262)	(0.00400)	(0.000490)	(0.00246)	(0.00427)	(0.000568)	(0.00555)	(0.00406)	(0.000485)
Year cleared	−0.00217	0.00668	−0.00164	0.00452	0.0158	−0.00176	0.00230	0.0113	−0.00357
	(0.0121)	(0.0171)	(0.00290)	(0.0113)	(0.0181)	(0.00383)	(0.0195)	(0.0154)	(0.00279)
Slope	0.00555	−0.0193	−0.00460	0.00619	−0.0106	−0.00472	0.0127	−0.0324	−0.00522*
	(0.0155)	(0.0278)	(0.00284)	(0.0195)	(0.0371)	(0.00577)	(0.0312)	(0.0271)	(0.00310)

Table 5 continued

	Cattle excluded from assets			APA households excluded from sample			Farm income only		
	(1) Ln (Income)	(2) Assets	(3) Ln (Cleared)	(4) Ln (Income)	(5) Assets	(6) Ln (Cleared)	(7) Ln (Income)	(8) Assets	(9) Ln (Cleared)
Soil suitability	−0.0790	0.111	−0.0126	−0.0704	0.135	−0.0112	−0.257	0.125	−0.0143
	(0.0848)	(0.181)	(0.0162)	(0.0763)	(0.173)	(0.0204)	(0.159)	(0.162)	(0.0167)
Year arrived in Rondônia	−0.00157	−0.00143	0.000522	−0.00130	−0.00374	0.000588	−0.0103	0.00903	−0.000250
	(0.00721)	(0.0169)	(0.00112)	(0.00785)	(0.0161)	(0.00127)	(0.0183)	(0.0149)	(0.00122)
Age	0.00124	−0.00259	−0.000295	0.00177	0.00486	−0.000496	−0.0107	0.00329	0.000503
	(0.00552)	(0.00714)	(0.000877)	(0.00477)	(0.00766)	(0.000905)	(0.0114)	(0.00734)	(0.000931)
Education	0.0181	−0.0327	−0.00490	−0.00805	−0.00118	−0.00361	0.0145	−0.00743	−0.00466
	(0.0295)	(0.0400)	(0.00538)	(0.0252)	(0.0428)	(0.00596)	(0.0538)	(0.0406)	(0.00536)
South/Southeast	0.0886	−0.264	−0.00592	0.187	−0.294*	−0.0388	0.312	−0.313*	−0.00617
	(0.155)	(0.174)	(0.0345)	(0.159)	(0.171)	(0.0384)	(0.348)	(0.168)	(0.0341)
Family size	−0.0112	0.0830***	0.000632	−0.00798	0.0672**	−0.000239	−0.0178	0.0863***	0.000505
	(0.0107)	(0.0285)	(0.00165)	(0.0122)	(0.0269)	(0.00208)	(0.0241)	(0.0245)	(0.00170)
2005	−0.134	0.118	−0.00915	−0.244	0.165	0.000144	−0.307	0.0811	−0.00804
	(0.149)	(0.258)	(0.0185)	(0.165)	(0.230)	(0.0197)	(0.221)	(0.251)	(0.0217)
2009	−0.00674	0.626**	−0.00194	−0.136	0.475*	0.00529	−0.410	0.609**	−0.00191
	(0.177)	(0.270)	(0.0299)	(0.193)	(0.264)	(0.0312)	(0.299)	(0.267)	(0.0334)
Observations	318	318	318	279	279	279	318	318	318
Hansen p value	0.448	0.0396	0.311	0.444	0.0912	0.704	0.277	0.0530	0.0415
Diff-in-Hansen	0.527	0.0699	0.646	0.561	0.280	0.552	0.588	0.271	0.558

Standard errors in parentheses, $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.0$
All estimated using System Generalized Method of Moments

practice, we find that none of these property or household characteristics have a statistically significant impact on land conversion. We also do not find that forest clearing varies with income or wealth. In other words, while agricultural conversion increases income and assets in a given time period, we do not observe feedbacks in the form of increases or decreases in land use change in response to changes in income or assets.

In Table 5, we assess the sensitivity of the System-GMM results to sample selection and alternative measures of wealth and income. The first set of results use a principal component index for assets that excludes cattle, on the grounds that head of cattle may be mechanistically related to agricultural expansion as land must be cleared to graze cattle. The results are broadly similar, although the model without cattle shows a smaller impact of income on assets than the model with cattle included, reflecting the importance of cattle as an investment during the time period of this study. There is no difference in the estimated relationship between cleared land and assets. The second set of results is based on just the random stratified sample, omitting the supplemental sample of Association of Alternative Producers (APA) members. We observe a slightly smaller impact of cleared land on household income, but otherwise the results are very similar to the results with the full sample.

The results in columns 7 to 9 consider income only from agriculture ($\mathrm{p_a q_a} - p_x \mathrm{x}$ in the theoretical model), excluding non-agricultural sources of income such as small businesses, sale of forest products, employment, pensions and welfare payments. As expected, given the role of cleared land in the production function, its impact on agricultural income is substantially larger than its impact on total income: a 10% increase in cleared area generates an 11% increase in agricultural income. The effect of assets on agricultural income is also greater than the effect of assets on total income, suggesting that our asset index—which includes many multi-purpose assets like vehicles—is particularly relevant to agricultural production. In the asset model, an additional dollar of agricultural income has a smaller effect on assets than an additional dollar of total income. Despite these differences, our overall conclusions about the impacts of agricultural expansion on income and wealth in the short and long run remain the same.

7 Conclusions

State-sponsored frontier colonization projects have generated substantial deforestation and related losses in tropical forest ecosystem services. Many are skeptical about the extent to which these losses are offset by local income gains and whether the local gains can be translated into broader development. We examine the evidence in a setting considered to have favorable conditions for agricultural colonization relative to many other places: the agrarian reform settlements in Ouro Preto do Oeste, Rondônia.

Over the 13-year study period from 1996 to 2009, there were both progressive gains in household income and assets and progressive expansion of agricultural land at the expense of forests. The question is whether this represents a causal relationship between clearing land and welfare, or results from time and space dependencies that influence both outcomes. As predicted by our theoretical model of optimizing households, in our empirical results we find a significant and positive impact of cleared land on household income, even after accounting for the simultaneity inherent in the relationship. Those who clear more forest earn higher incomes, reflecting the fact that the main income sources in this region require cropland or pasture.

The estimated marginal effect of clearing additional land in 2009, R$185/ha, is less than either total household income, or agricultural income, per hectare of cleared land,[13] because it conditions on past income and wealth as well as other determinants of household income. In this region, already heavily deforested in 1996, the clearing of additional hectares of forest land does not add much to income relative to average earnings from all previously cleared land. This result reflects the fact that, while agriculture remains important, households earn income from multiple other sources, including off-farm businesses, processed goods, forest products, and aquaculture. It also reflects diminishing marginal returns to additional expansion of agricultural area, particularly while other inputs such as human and physical capital are held constant.

A key contribution of this paper is estimation of the impacts of additional agricultural land on household assets, a more stable measure of household welfare than income, and one that may also be more indicative of the future trajectory of wellbeing because it contributes to future income generating capacity. We find that when we control for income, agricultural expansion has no direct effect on physical assets. This may be because returns to assets are not affected by changes in the area of cleared land within the ranges observed in our sample (90% of the properties have at least 18 HA of cleared land in all four periods). Alternatively, it may be because other determinants of investment such as overall asset productivity, discount rates, or prices, dominate any interactions between land and capital in the agricultural production function. Despite finding that agricultural expansion does not directly affect physical assets, we do find that cleared land increases assets indirectly via increases in income. This results from the strong positive relationships between cleared land and income, and between income and assets. This indirect effect appears to be large in practical terms, with a 0.2 standard deviation increase in cleared land leading to a 0.92 standard deviation increase in assets.

Our modeling approach also allows us to examine dynamic feedbacks between income, assets and cleared land. We do not find that changes in income or assets alter subsequent rates of forest clearing, i.e. there are no tendencies for clearing to either accelerate or slow as households get richer. However, we do find dynamic feedbacks in the accumulation of wealth that magnify the welfare benefits of agricultural expansion. As noted, converting forested to agricultural land is associated with accumulation of household assets through the mechanism of higher income. Additional assets enable households to accumulate still more assets, in a variation on the adage that the rich get richer. If we incorporate these feedbacks, the estimated long term impact of forest clearing on wealth is significantly larger than the short term impact.

From these results, we conclude that clearing additional forest in heavily deforested regions has a positive, but limited, effect on income. However, because that additional income is partly invested in physical assets, the effects on wealth, particularly in the long term, can be large due to the positive feedbacks between current income and current and future wealth. This

[13] Total income/cleared hectares in 2009 = R$24,367/70ha = R$348/ha; Agricultural income/cleared hectares in 2009 = R$19,866/70ha = R$284/ha.

implies that where INCRA settlement programs function as intended (with suitable land, secure property rights, and households remaining on the properties they were allocated), income from agricultural expansion provides an impetus for asset accumulation that can be self-perpetuating. It also highlights the importance of considering the indirect and long-term welfare benefits of agricultural expansion when assessing the opportunity costs of forest protection, rather than focusing solely on the immediate value of agricultural production on cleared land.

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Appendix: Sources of growth in the Ouro Preto do Oeste region

Municipalities throughout the Amazon are experiencing increases in income and welfare that exceed national averages (Caviglia-Harris et al. 2016), but the sources of this growth vary by region and state (Table 6). The dairy sector has been an important engine of economic growth in Ouro Preto do Oeste. This reflects a general trend towards ranching throughout the Brazilian Amazon (Bowman et al. 2012; Soares-Filho et al. 2009; Mertens et al. 2002), but the cattle herd has grown exceptionally fast in Rondônia and Ouro Preto do Oeste, with over 40 and 50% growth in the 1990s and 2000s. Although the agricultural economy of Ouro Preto do Oeste is unusual in its emphasis on dairy, other regions have also achieved rapid agricultural growth by specializing in commodities such as soy, sugar cane, or black pepper.

Table 6 Agricultural Trends in Amazonian Municipalities with different histories of agrarian reform settlements; 1991–2010

	Obs.	Area (1, 000 km^2)	Cattle (head, 1,000)	Dairy (head, 1,000)	Soy (Kt)	Sugar (Kt)	Black pepper (Kt)	Percent change[1] cattle	Percent change Dairy	Percent change soy	Percent change sugar	Percent change black pepper
1991												
Greater Ouro Preto do Oeste	6	6.3	198	39	0	0	0	NA	NA	NA	NA	NA
Other municipalities with pre-1993 settlements	164	1,286	10,970	1,075	303	1,302	16	NA	NA	NA	NA	NA
Municipalities with post-1992 settlements	335	2,413	12,520	974	1,851	2,865	42	NA	NA	NA	NA	NA
Municipalities with no settlements	266	1,352	5,184	367	603	620	18	NA	NA	NA	NA	NA
2000												
Greater Ouro Preto do Oeste	6	6.3	635	84	0	785	0	220.97	112.02	NA	NA	NA
Other municipalities with pre-1993 settlements	164	1,286	15,784	900	585	1,188	18	43.89	−16.25	92.77	−8.74	14.48
Municipalities with post-1992 settlements	335	2,413	22,560	1,016	5,943	7,548	11	80.19	4.33	221.05	163.48	−74.56
Municipalities with no settlements	266	1,352	8,245	458	2,885	1,597	5	59.06	24.84	378.61	161.80	−74.23

Table 6 continued

	Obs.	Area (1,000 km^2)	Cattle (head, 1,000)	Dairy (head, 1,000)	Soy (Kt)	Sugar (Kt)	Black pepper (Kt)	Percent change[1] cattle	Percent change Dairy	Percent change soy	Percent change sugar	Percent change black pepper
2010												
Greater Ouro Preto do Oeste	6	6.3	973	222	0	1,515	0	53.17	164.78	NA	92.99	NA
Other municipalities with pre-1993 settlements	164	1,286	25,966	1,343	2,100	1,256	9	64.52	49.15	259.11	5.74	−49.67
Municipalities with post-1992 settlements	335	2,413	38,097	1,526	12,338	12,611	19	68.87	50.25	107.61	67.09	73.81
Municipalities with no settlements	266	1,352	12,397	66	7,206	4,790	12	50.36	44.47	149.78	199.97	149.26

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