# Recent transformations of land-use and land-cover dynamics across different deforestation frontiers in the Brazilian Amazon

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## ABSTRACT

After forest governance reforms by the Brazilian government, Amazon deforestation rates dropped by almost 80% between 2004 and 2012. Since then, however, deforestation has slowly increased again, casting doubts on the long-term sustainability of past conservation policy achievements. Clearly, deforestation rates and the associated local drivers of land-use and land-cover change differ considerably across the region, and adapting public policies to dynamic local contexts and actor constellations remains a major challenge for decision-makers. This paper seeks to contribute to the related science-policy debate by applying frontier theory insights to map, quantify, and compare land-cover dynamics in the Brazilian Amazon between 2004 and 2015. Our theoretical framework performs well in explaining broad variations in scope, nature, and agents of land-use and land-cover change across different frontier regions. We observe two types of transformative processes at deforestation frontiers in the Amazonian context. First, recent frontier development is characterized by an intensification of cattle ranching, and an increasing share of agricultural activities in the production portfolio, which could be the result of better access to modern technologies and markets, combined with forest governance induced scarcity of land for expansion of historically dominant extensive pasture systems. Second, the share of medium and large-scale deforestation declines at first, but rebounds during the observation period in all frontier types after 2012. Further research is needed to better understand the role of the changing political environment in driving these medium and short-term transformations in land-use and land-cover change. Furthermore, policy-makers, international cooperation, and civil society must seek strong integration between value chain based governance measures and effective environmental law enforcement.

## 1. Introduction

Frontier theory is a prominent conceptual framework to analyze and describe the dynamics of land-use and land-cover change (LUCC) in tropical rain-forest areas (Faris 1999; De Koninck, 2000; Entwisle et al., 2008; Barbier, 2012; Pacheco, 2012). Frontiers can be generally framed as "regions just beyond or at the edge of human settlement" (Merriam-Webster, 2004), where multiple land-conversion processes take place that are characterized by the substitution of natural vegetation with domesticated plants for food and feed production. Deforestation is among the most commonly studied phenomena in the frontier literature, as it is often associated with negative impacts on the global climate, biodiversity, and local as well as regional hydrological cycles (Werth and Avissar, 2002; Fearnside, 2005; Foley et al., 2005; Intergovernmental Panel on Climate Change, 2013).

One strength of frontier theory is the focus on a set of processes and underlying causal relationships that are specific to remote areas with distinct geographical and social characteristics, for example, in studies on deforestation and environmental change. In the past three decades, multiple theoretical approaches have been proposed to link different causal drivers to frontier development at local scale. This theoretical diversity has become a powerful toolkit to describe LUCC trajectories across different socio-economic settings, for example, in the Amazon region (Fearnside, 2001; Walker et al., 2002; Pacheco, 2005; Aldrich et al., 2006; Jepson, 2006; Caldas et al., 2007; VanWey et al., 2007; Browder et al., 2008; Michalski et al., 2010; Carrero and Fearnside, 2011). Case-study based explanatory richness comes with a desirable conceptual pluralism, but it faces limitations in terms of representativeness and cross-case comparability. Given the technical, financial, and political constraints of policy making at national scale, decision-makers can benefit from spatially explicit landscape and regional scale approaches, when targeting heterogeneous frontier conditions (Sayer et al. 2013). Pacheco (2012), for example, has mapped deforestation frontiers in the Brazilian Amazon describing frontiers in terms of land-

cover and actor characteristics, using data aggregated at municipality level. He classifies frontiers based on their deforestation levels and identifies priority areas for policy action. Along a gradient of deforestation, however, frontier theory suggests considerable changes in the relative importance of the proximate and underlying causes of deforestation (Angelsen 2007; Walker 2012). Policy design may thus benefit from a theory informed selection of classification variables.

A number of recent studies have, moreover, analyzed policy effects on recent deforestation dynamics at regional scale (Assunção et al., 2012; Arima et al. 2014; Börner et al., 2014; Gibbs et al., 2015a,b). These studies have generally found that the Brazilian government adopted effective policy instruments after Amazon deforestation rates had peaked between 2003 and 2004. However, designing a policy mix that promotes long-term sustainable forest transition pathways requires a more comprehensive understanding of how land-use systems have changed in response to forest governance reform (Barbier et al., 2010).

Hence, this paper aims to inform national and subnational decision makers by (1) developing a theory-based, spatially explicit frontier classification for the Brazilian Amazon, and (2) analyzing frontier-specific land-use change dynamics for the period of 2005 until 2015. For this purpose, we have developed a theoretical framework that builds on key insights from frontier literature, as well as case study evidence from the Brazilian Amazon. Our framework, inspired by Von Thünen's model of agricultural land rents, is presented in Section 2.

Our methodological approach and the construction of a spatial database to map frontier regions and quantify LUCC is presented in Section 3. Results are presented in Section 4, where we identify eight different frontier types, characterized by distinct LUCC dynamics and socio-economic characteristics. Although those frontier characteristics correspond to most of our theoretical expectations, we observe a predominance and persistence of cattle ranching in all frontier types, which deviates from frontier theory predictions. However, our results also indicate a frontier-wide paradigm-shift towards more intensive cattle production and an increase in annual crop production. Section 5 discusses our findings and theoretical shortcomings of our proposed model. Section 6 draws conclusions against the backdrop of the current political and economic context of land-use change in Brazil and beyond.

## 2. Theoretical background

The conversion of primary forest to cropland or pastures is commonly framed as an investment decision driven by expected returns to alternative uses or future appreciation of land values (Dias et al., 2016). However, as we move from well-established agricultural landscapes to remote frontier regions, expectations related to return on investment are based on very different socio-economic realities. Our conceptual framework assumes that market-distance and accessibility are a key underlying determinant of deforestation, and is therefore based on Johan Heinrich Von Thünen's model of agricultural land rents. In this model, Von Thünen assumes a homogeneous state characterized by a central market, uniform biophysical conditions, and no foreign trade. Transportation costs increase with distance to the market and agricultural goods have a limited durability. This leads to a distribution of land-use classes that follow a pattern of concentric circles with more input-intensive and perishable cultures in the inner circles, and extensive land-uses with less perishable products, such as livestock and wood production, in the outer circles around the market (von Thünen, 1910).

The standard Von Thünen model characterizes the distribution of land-use classes in a steady state, where all land has already been converted and assigned to its most profitable purpose. This contrasts with the dynamic nature of land-use change at forest frontiers, as infrastructure and market access improve over time. In the extended Von Thünen framework presented in Fig. 1, agricultural land-use expands geographically into more remote areas as the frontier develops and urban centers grow over time. The distribution of land-conversion is
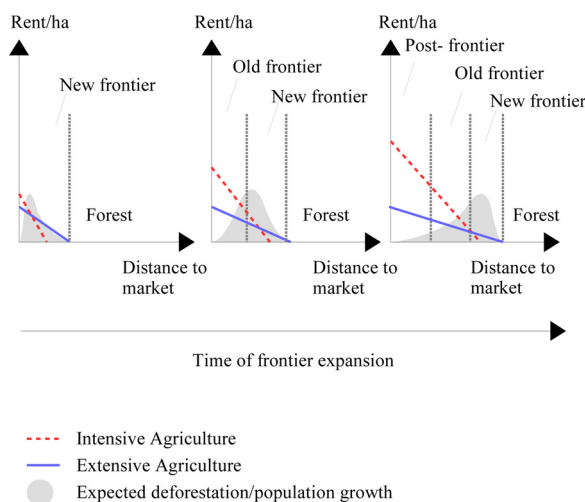


**Fig. 1.** Population change and deforestation in a time-dependent land-rent model.

dependent on the profitability of different land-use forms, which is dependent on its current distance to the next market and the local market demand (see Fig. 1).

Following Fig. 1, the spatial location of deforestation changes over time as frontier development advances, with the highest deforestation rates occurring in new frontier areas. However, since deforested area accumulates over time, more deforested areas are found in older frontiers compared to newer frontier regions. If new frontiers attract additional settlers, a similar demographic development pattern is expected, with population increases in recent deforestation frontiers and decreasing rural population growth after a certain amount of frontier development. This conjecture is in line with structuralist approaches of frontier theory, although the driving forces behind this development are rooted in economic, as well as demographic changes in local family structures over time (Perz 2003; VanWey et al., 2007; Browder et al., 2008). Consistent with the Von Thünen model, more intensive land-use forms predominate regions that have better access to markets, and frontier development comes along with the replacement of extensive land-use forms with more intensive land-uses - especially in areas close to urban markets.

Despite infrastructure improvements and subsequent population growth, another important factor for frontier development is governance. Policy factors matter, because they can influence land-rents and thereby distort the development of deforestation frontiers (Barbier et al., 2010). In the context of Brazil, planned settlement projects play a crucial role in regional development and land conversion (de Almeida, 1992; Goza, 1994; Moran, 1997; Fearnside, 2008; Pacheco, 2009b). In addition to securing property rights, these projects were thought to come along with infrastructure investments and agricultural extension programs intended to provide settlers with credit, know-how, and production inputs. Despite widespread implementation failures (Pacheco, 2009a), settlement projects were found to promote forest conversion due to higher land rents and policy-induced migration to remote rural areas (Schneider and Peres, 2015). In addition to increased land conversion, we also expect, that the scale of individual deforestation activities is smaller in settlement projects than for other frontier types, because settlers tend to face binding capital and land constraints. Because of these limitations, settlement frontiers are dominated by subsistence-oriented production and/or extensive land-use forms like cattle ranching.

The cultural background of settlers has repeatedly been subject to debates in the literature on Amazon colonization. Farmers, who migrate to the Amazon from the Brazilian South, were shown to prefer different production systems than peasants from the poorer north or north-east of