

Cutting Down Trees Does not Build Prosperity: On the Continued Decoupling of Amazon Deforestation and Economic Development in 21st Century Brazil


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Source: Tropical Conservation Science, 15(1)

Published By: SAGE Publishing

URL: <https://doi.org/10.1177/19400829221132193>

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Tropical Conservation Science
Volume 15: 1–15
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DOI: 10.1177/19400829221132193
journals.sagepub.com/home/trc


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Abstract

Background and Aims: We present evidence examining spatial and temporal patterns in forest cover changes and economic indicators in Brazilian Amazonia. Specifically, we tested two predictions embedded in arguments used by influential interest groups: (i) indicators of economic progress should increase where there is less forest and (ii) areas with most recent deforestation should have increased economic indicators.

Methods: Complementary methods assessed annual variation in economic indicators across 794 administrative districts (municipalities) covering 4.9 Mkm² of the Brazilian Amazon from 2002 to 2019. A representative subset of municipalities was used to compare economic and socioeconomic indicators across municipalities with contrasting forest cover.

Results: Contrasting results between the full and a representative subset of municipalities suggested that municipality-level economic indicators cannot be directly attributed to the loss of natural forests. There was no association between forest loss and economic (average salary) or socioeconomic indicators (existence of sanitation plans and internet connectivity). The economic indicators of municipalities with less than 40% forest cover in 1986 were no different to that of similar municipalities with more than 60% forest cover from 1986 to 2019.

Conclusion: The evidence contradicted both predictions tested. Reducing forest cover does not appear to directly promote socioeconomic progress. Any localized associations between forest cover and poverty most likely result from other more plausible alternatives including lack of opportunity and a widespread failure to effectively implement and enforce existing policies within the local socioeconomic context.

Implications for Conservation: Our findings support evidence from across the tropics that shows deforestation does not necessarily generate transformative and equitable food production systems or lead to poverty alleviation.

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Received: 16 May 2022; revised: 25 September 2022; accepted: 26 September 2022

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Résumé

Contextualização e Objetivos de Pesquisa: Apresentamos evidências examinando padrões espaciais e temporais nas mudanças de cobertura florestal e indicadores econômicos na Amazônia brasileira. Especificamente, testamos duas predições contidas em argumentos usados por influentes grupos de interesse: (i) onde há menos floresta os indicadores de progresso econômico devem aumentar e (ii) áreas com desmatamento mais recente devem ter melhores indicadores econômicos.

Métodos: Métodos complementares foram utilizados para avaliar a variação nos indicadores econômicos em 794 distritos administrativos (municípios) cobrindo 4.9 Mkm² da Amazônia brasileira de 2002 a 2019. Um subconjunto representativo de municípios foi usado para comparar indicadores econômicos e socioeconômicos entre municípios com cobertura florestal contrastante.

Resultados: Resultados contrastantes entre o total e um subconjunto representativo de municípios sugerem que os indicadores econômicos em nível municipal não podem ser atribuídos diretamente à perda de florestas naturais. Não houve associação entre perda florestal e indicadores econômicos (salário médio) ou socioeconômicos (existência de planos de saneamento e conectividade à internet). Os indicadores econômicos de municípios com menos de 40% de cobertura florestal em 1986 não foram diferentes dos de municípios semelhantes com mais de 60% de cobertura florestal no período de 1986 a 2019.

Conclusão: As evidências contradizem ambas as predições testadas. A redução da cobertura florestal não parece promover diretamente o progresso socioeconômico. Quaisquer associações locais entre cobertura florestal e pobreza provavelmente resultam de outras alternativas mais plausíveis, incluindo falta de oportunidade e uma falha generalizada na implementação e aplicação efetiva das políticas existentes no contexto socioeconômico local.

Implicações para a Conservação: Nossas descobertas apoiam evidências encontradas em todos os trópicos que mostram que o desmatamento não gera necessariamente sistemas de produção de alimentos transformadores e equitativos ou leva ao alívio da pobreza.

Keywords

Amazon, agriculture, deforestation, economics, forest loss, gross domestic product, gross value added, income, Mapbiomas, land cover, poverty, prosperity, socioeconomics, sustainable development

Highlights

- No evidence of direct associations between forest loss and socioeconomic progress indicators.
- Approximately 292,000 km² of natural forest cover was lost between 2002 and 2019.
- By 2019 only 9% of municipalities had both approved sanitation plans and full internet connectivity.

Background: Forest loss, agriculture and poverty in Brazilian Amazonia

In 2021, deforestation in the Brazilian Amazon increased to the highest level since 2006 (Butler, 2021), while the contribution of agribusiness to the Brazilian Gross Domestic Product (GDP) declined to its lowest level since 2012 (Amorim et al., 2021; Crelier, 2021). Yet at the same time, the Brazilian national statement to the 2021 United Nations Climate Change Conference asserted that “where there is a lot of forest there is also a lot of poverty” (Brazil, 2021)—implying a direct cause-effect relationship between forest cover and poverty in 21st century Brazil. While such statements follow a mainstream narrative of environmental

destruction as a “necessary cost” of development, they do not align with a growing evidence base demonstrating relationships between 21st century deforestation and human development are complex and dynamic (Borda-Niño et al., 2020; Busch & Ferretti-Gallon, 2017; Fischer et al., 2020; Lambin et al., 2018; Meyfroidt et al., 2022). These complex dynamics have been demonstrated at regional (Caviglia-Harris et al., 2016; Kauano et al., 2020; Silva et al., 2017) and local scales (Mullan et al., 2018). However, pathways to increase prosperity and reduce poverty remain uncertain across Brazilian Amazonia (Alves-Pinto et al., 2015; Garrett et al., 2021; Silva et al., 2017).

Poverty, as defined by the United Nations is a denial of choices and opportunities resulting in a lack of basic capacity to participate effectively in society. Poverty in capitalist societies is often linked with economic “capacity” through measures such as GDP and income (World Bank, 2022). Yet, economic capacity may not guarantee poverty alleviation. This has been argued in the case of expansion of the agricultural frontier in regions of Brazil where the use of monocultures, mechanization, and land concentration has resulted in displacement and exclusion of local populations, social conflicts, and the loss of subsistence and access to

resources that used to belong to the traditional local populations (Sauer, 2018). And so, as evidenced by Russo Lopes et al. (2021) the improvement of economic indicators can reveal maldevelopment, which implies unequal and exclusive change processes that deprive most local actors, particularly the most vulnerable, of their social and material capacities. Nonetheless, economic mechanisms to reduce poverty represent key aspects of Brazilian post-colonial society (Naritomi et al., 2012), both historically (a national minimum salary was implemented in 1938 by president Getúlio Vargas) and more recently via cash transfer programs established after the 1988 Constitution. For example, “Bolsa Escola” was implemented in 2001 by the government under Fernando Henrique Cardoso, and expanded by president Luís Ignacio da Silva as “Bolsa Família” and most recently “Auxílio Brasil” under the current president Jair Bolsonaro (Ministério da Cidadania, 2022). Despite these actions, it is estimated that in 2018 approximately 23 million people lived below the poverty threshold in Brazil (FGV social, available at <https://cps.fgv.br/Pobreza-Desigualdade>, accessed 11 May 2022).

People experiencing poverty may go without basic necessities such as proper housing, clean water, medical attention, and access to healthy food. Meeting present and future needs to simultaneously increase food access and reduce biodiversity loss is a critical component of Sustainable Development Goals and the Post 2020 Global Biodiversity Framework (CBD, 2021) to which Brazil is party. Indeed, loss of rainfall and climate changes associated with continued Amazon deforestation (Lovejoy & Nobre, 2018) are likely to generate not only reduced revenue but also irreversible losses in the agricultural capacity to meet the needs of future generations (Leite-Filho et al., 2021; Tanure et al., 2020). At the same time, the continued concentration of relatively poor rural populations on degraded and poorly productive agricultural land has implications not only for the living standards of millions of rural households but also for poverty alleviation (Barbier & Di Falco, 2021).

Although an economic focus for examining poverty alleviation remains debatable, the timing of such a focus is relevant, considering the upcoming presidential election in Brazil, which is one of the world’s largest democracies and economic powers (EIU, 2021). Despite decades of studies, it remains intensely debated whether the erosion of environmental protection as measured via forest loss (the most obvious measure of protection) is economically and socially justifiable (Abessa et al., 2019; Bastos Lima et al., 2021; Silva Junior et al., 2020). Here, we compile evidence to test two predictions that follow from the Brazilian national statement, which implied a direct cause-effect relationship between forest cover and poverty. First, economic indicators should be greater where there is less forest cover relative to areas with more forest cover. Second, the population within areas with the most recent deforestation should have higher average salaries and improved socioeconomic indicators compared to places with less recent deforestation.

We evaluated annual changes in forest cover together with economic and socioeconomic indicators to test the two predictions across administrative districts (municipalities). The analysis included municipalities from nine states to reflect the Brazilian political and administrative hierarchy (Figure 1). Hereafter the region covered by the nine states is referred to as Brazilian Amazonia. Diverse forest types are found within and among the municipalities, including those from Amazon and Cerrado (savanna) biomes. For this analysis, we included both natural forest and savanna vegetation types as forest cover (MapBiomias 2021). The most up to date forest cover and economic data from 2002 to 2019 (IBGE, 2021; MapBiomias 2021) was used to test predictions both across 794 municipalities covering 4.9 M km² and a subset of 357 municipalities (877 K km²). This subset was identified to isolate the effects of forest cover and loss since 1985 (see Methods for subset selection details). The 357 municipality cover class subset included a resident population of 7,988,731 in 2019 (37.8% of the overall resident population across 794 municipalities in 2019). Only 6 of the 357 municipalities included an urban concentration (see Methods for full details of municipality characteristics). The data and code used to produce the analysis and figures are available from Norris (2022).

Forest loss is not associated with economic indicators

Continued deforestation in Brazilian Amazonia is largely driven by economic and political interests (Garrett et al., 2021; Schneider et al., 2021). The pace and scale of forest loss across Brazilian Amazonia are not constant due in large part to the high cultural, social, and environmental heterogeneity. Between 2002 and 2019 median Gross Domestic Product (GDP) per capita increased more than fivefold (from 679 to 3401 US\$) and agriculture Gross Value Added (GVA) per capita increased nearly fourfold over the same period (from 149 to 536 US\$). In contrast, the median salary remained relatively stagnant, increasing from 1.7 to 1.9 times the national minimum salary value from 2006 to 2019 (1.9 corresponded to an average salary of R\$ 1862 or US\$ 472 per month in 2019). This stark contrast among rates of increase is a clear indication of the profound inequalities that continue to surround economic maldevelopment across Brazilian Amazonia (Garrett et al., 2021; Russo Lopes et al., 2021).

Deforestation has been accompanied by an economic recession in Brazil, which according to Nobre and Nobre (2018) shows the decoupling of deforestation with economic growth. A total of approximately 292,194 km² of natural forest cover was converted to human land use from 2002 to 2019 (Figure 2). Correlations among summarized annual economic indicators and forest loss values were weak and not significant (Spearman rho = 0.26, 0.15, 0.52 for GDP per capita, agriculture GVA per capita, and average salary, respectively, $P > 0.05$). Economic indicators at the level of municipalities were also very weakly correlated with forest loss over the same

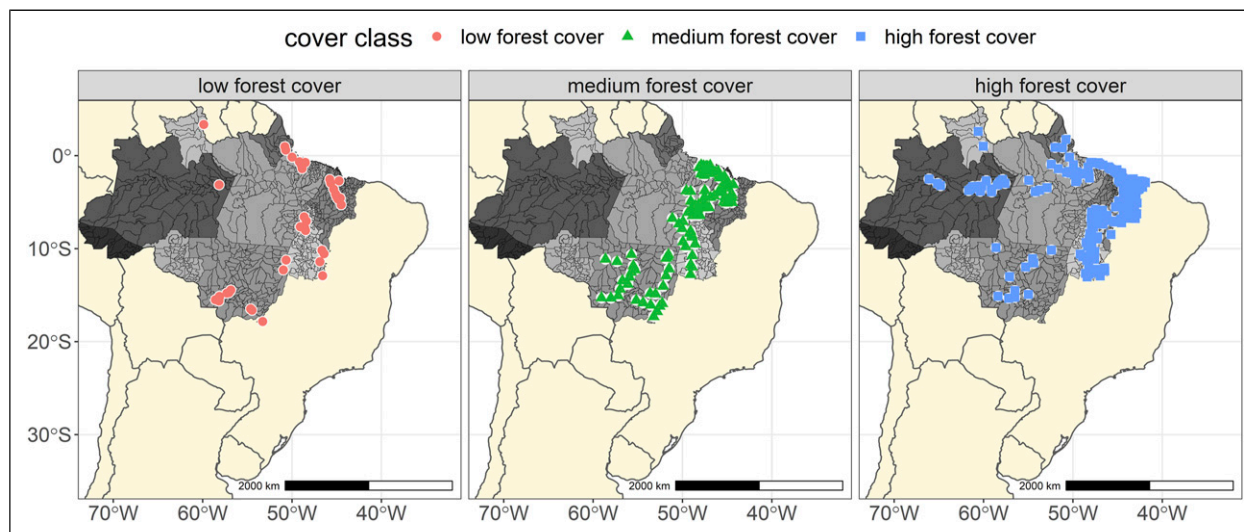


Figure 1. Study area. Brazilian Amazonia in South America. Showing nine Brazilian states in gray shading with gray lines showing municipality borders. Colored symbols show locations of the subset of 357 municipalities used to isolate effects of forest cover change on socioeconomic indicators. This cover subset was grouped into three forest cover classes using percent of natural forest cover in 1986 as a reference level (“low”: less than 40%, “medium”: more than 60% in 1986 but less than 50% in 2019 and “high” more than 60% in 1986 and 2019 [full subset details in Methods]). Symbol sizes have been enlarged to aid visualization and locations can overlap.

period (Supplemental Material S1). Analysis controlling for spatial and temporal autocorrelations showed weak and insignificant associations of forest loss expressed as both km² and proportion of forest cover in 1986 and economic indicators (Supplemental Material S2 for full model results). Further studies are required to examine these patterns in more depth to understand the contribution of other factors including industrial activities (e.g., construction, hydropower dams, and mining) that are likely to contribute to the variation in socioeconomic indicators across the 794 municipalities (Abessa et al., 2019; Busch & Ferretti-Gallon, 2017; Caviglia-Harris et al., 2016; Garrett et al., 2021; Stabile et al., 2020).

Analysis across the representative subset of 357 municipalities indicated no significant difference in economic indicators from 2006 to 2019 among forest cover classes (Figure 3). This analysis is the first we are aware of that provides empirical evidence for the continued decoupling of economic indicators and forest loss across Brazilian Amazonia controlling for both temporal and spatial autocorrelation. Controlling for spatial and temporal autocorrelations confirmed that there were no statistical differences in agriculture GVA per capita, GDP per capita, or salary among the three cover classes (Generalized Additive Models [GAMs], $P > 0.12$ for cover classes explaining agriculture GVA per capita, GDP per capita and salary, Supplemental Material S3 for model results). The same comparison made using the longer time series (2002–2019) for GDP and agricultural GVA per capita also showed no statistical difference in economic indicators among the three cover classes. There was no evidence of differences in sample sizes or unobserved omitted selection variables generating any systematic bias (Supplemental Material S5).

Forest loss is not associated with socioeconomic indicators

Current economic development paths are leading not only to forest loss but may also lead to poverty and increased conflicts across Brazilian Amazonia (Bastos Lima et al., 2021; Rodrigues et al., 2009; Silva Junior et al., 2020). Continued agribusiness development arises (at least in part) from decades without viable economic alternatives across Brazilian Amazonia (Garrett et al., 2021; Schneider et al., 2021). Agribusiness development is widespread, with regions experiencing agribusiness development including states not only with rapidly expanding deforestation such as Tocantins, but also the most protected Brazilian state Amapá (Schneider et al., 2021). In addition to environmental degradation, current agribusiness production chains have limited inclusiveness for the rural poor (Ferrante & Fearnside, 2019; Garrett et al., 2021; Russo Lopes et al., 2021). It is therefore unsurprising that only 8.7% of 794 municipalities (with a median fivefold increase in GDP over 18 years) had both an approved sanitation plan and complete internet connectivity among administrative centers by 2019 (see Methods for definitions of sanitation plan and complete internet connectivity).

There was complete internet connectivity among the administrative centers in less than half (40.9%) of municipalities and less than one in five municipalities (19.9%) had a sanitation plan approved by 2019 (Figure 4). Forest loss (% of 1986 area) between 1986 and 2019 was the same among municipalities with or without these indicators, with similar central tendency and distribution of forest cover change among municipalities with or without the condition (Figure 4A). There

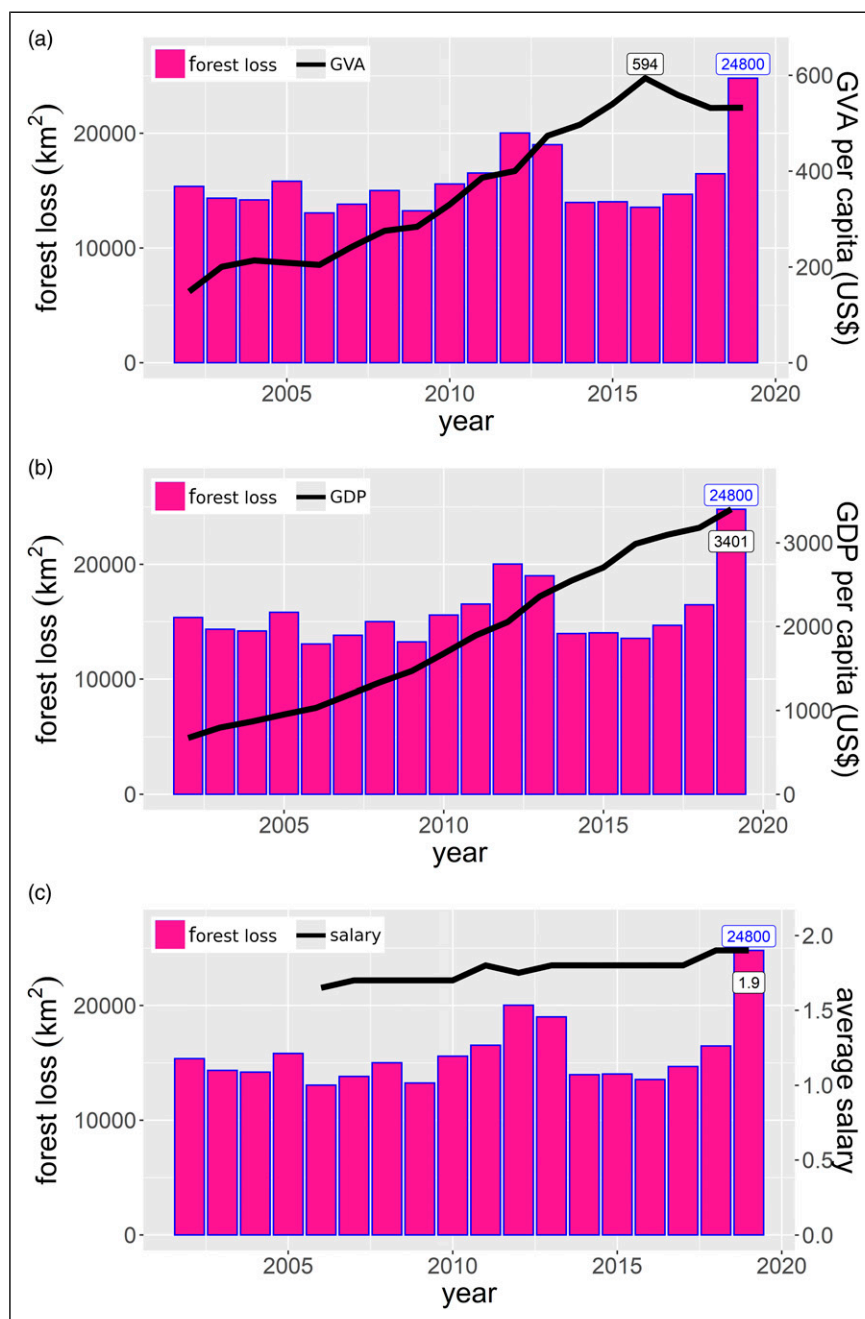


Figure 2. Economic indicators and forest loss in Brazilian Amazonia. Annual values of forest loss and (A) agriculture Gross Value Added per capita, (B) Gross Domestic Product per capita and (C) salaries from 2002 to 2019 across the Brazilian Amazon. The pink bars represent annual values of forest loss showing totals of transition from natural forest (including savanna and forest formations) to anthropogenic land uses (MapBiomias, 2021). Salaries expressed as a proportion of the annual minimum salary value (full details of economic indicators in Methods). Solid black lines are the median values from 794 municipalities. Text labels show maximum values for each series (blue for forest cover and black for economic indicators).

was also no significant difference in the proportion of municipalities with both a sanitation plan and complete internet connectivity among the three different forest cover classes (χ^2 1.44, $df = 2$ $P = 0.4876$, Figures 4C and D).

Changes in land use for food production can in some cases improve living conditions; however, extensive

change in forest cover does not seem to have a similar effect in the Brazilian Amazon. A widespread lack of basic conditions across Brazilian Amazonia is well documented. For example, a recent government report showed that only 58.9% of the population in the North region (comprising Acre, Amapá, Amazonas, Pará,

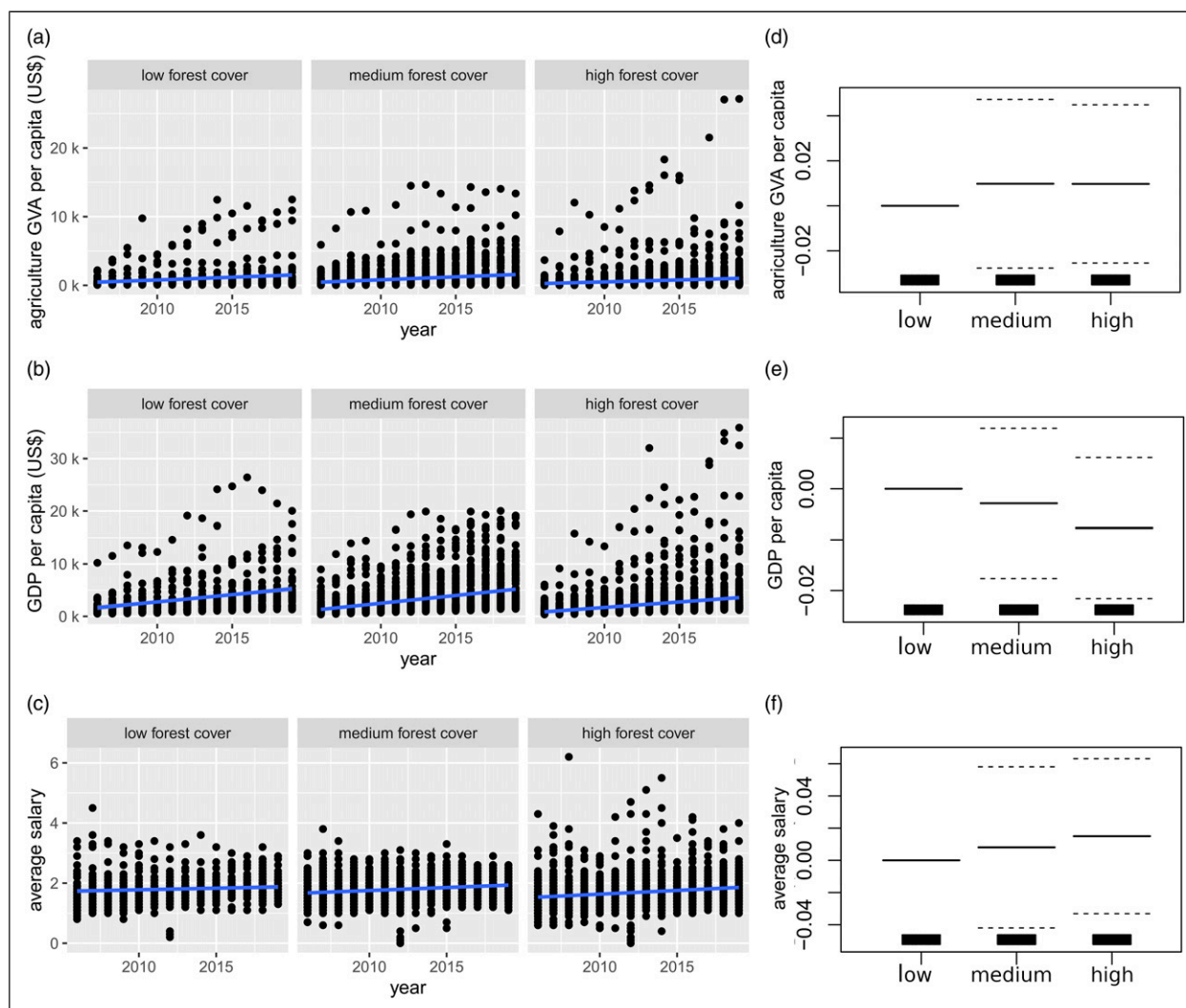


Figure 3. Economic indicators and forest cover change. Comparison of three economic indicators among forest cover classes. Annual trends from 2006 to 2019 (A–C) and GAM partial plots (D–F) of three economic indicators, row wise top to bottom: agriculture Gross Value Added per capita, Gross Domestic Product per capita and salaries (expressed as a proportion of the annual minimum salary value). These indicators are compared among a subset of 357 municipalities with contrasting proportions of natural forest cover. (A–C) Solid blue line is linear trend over time added to aid visual interpretation. (D–F) Partial plots show marginal effects of cover classes on the economic indicators. Marginal effects presented on the link scale, and centered about the model constant term (solid horizontal lines are mean values, dashed horizontal lines are 2X Standard Error of the mean). The subset was selected to isolate effects of forest cover change on economic indicators; with municipalities grouped into three forest cover classes using percent of natural forest cover in 1986 as a reference level (“low”: less than 40%, “medium”: more than 60% in 1986 but less than 50% in 2019 and “high” more than 60% in 1986 and 2019 [full subset details in Methods]).

Roraima, Rondônia, and Tocantins) had access to clean water by 2020 (MDR, 2021). Such failures were also reflected in a recent analysis that showed Brazil—a member of the G20 and the sixth most populous nation—ranked only 71 in an assessment of human capital that takes into consideration mortality and education (Lim et al., 2018). As there are clear systematic weaknesses in the current development trajectory, it is important to reinforce alternative sustainable development pathways that can accelerate poverty alleviation without deforestation (Carvalho et al., 2022; Garrett et al., 2021;

Moutinho et al., 2016; Stark et al., 2022). Additionally, as forest loss does not appear to benefit the municipalities where deforestation is happening, our analysis provides empirical evidence not only of continued decoupling but also of marked inequalities and maldevelopment across Brazilian Amazonia (Russo Lopes et al., 2021).

Although there is a solid theoretical background for the development of sustainable futures (Daw et al., 2011; Shyamsundar et al., 2020; Stark et al., 2022), examples of zero deforestation alternatives that meet present and future needs remain rare in tropical regions (Pinho et al., 2014). The

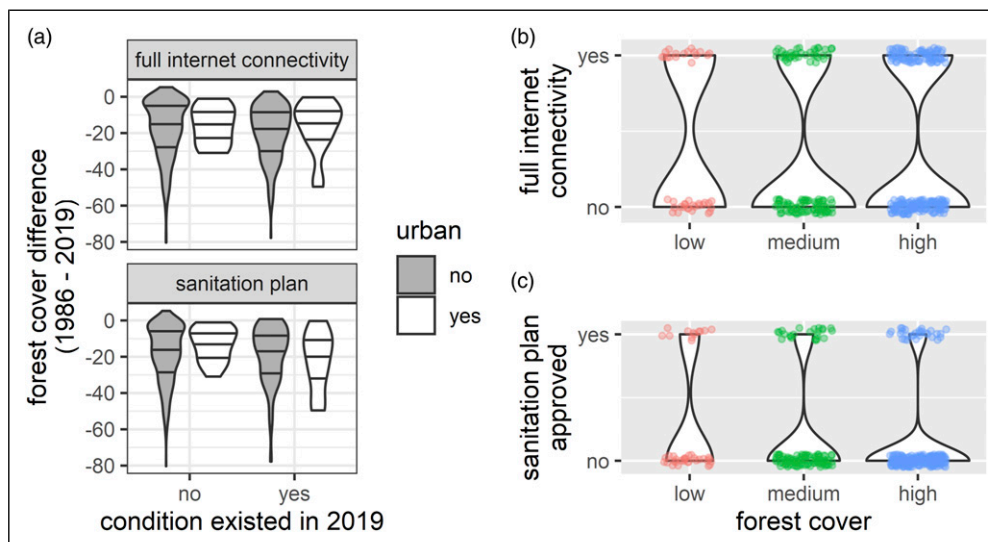


Figure 4. Forest loss and socioeconomic indicators. Comparison of the existence of two socioeconomic conditions and forest cover change among (A) all 794 municipalities and (B, C) representative subset of 357 municipalities. The subset was selected to isolate effects of forest cover change on socioeconomic indicators. This cover subset was grouped into three forest cover classes using percent of natural forest cover in 1986 as a reference level (“low”: less than 40%, “medium”: more than 60% in 1986 but less than 50% in 2019 and “high” more than 60% in 1986 and 2019 [full subset details in Methods]).

Brazilian government has committed to stop all illegal deforestation. However, given recent shortcomings in enforcing environmental legislation (Carvalho et al., 2022), such compromises may fall far short of ensuring not only the conservation of such vast natural capital for future generations but also commensurate improvements in local well-being before critical tipping points are reached (Bastos Lima et al., 2021; Boucher & Chi, 2018; Boulton et al., 2022; Carvalho et al., 2022; Ferrante & Feamside, 2019; Lovejoy & Nobre, 2018; Moutinho et al., 2016; Pereira et al., 2020; Silva Junior et al., 2020). Additionally, legal deforestation associated with agribusiness development can create inequalities; with zero illegal deforestation currently relying on market-based solutions. Research suggests however that market initiatives on their own, without additional measures including effectively enforced regulatory policies, will not achieve the environmental or social outcomes needed (Boulton et al., 2022; Moutinho et al., 2016; Pereira et al., 2020; Russo Lopes et al., 2021; Silva Junior et al., 2020).

Due to the heterogeneity and inequality that persists in the Brazilian Amazonia, government policies should facilitate the creation of diverse alternatives for sustainable development, exploring the underutilized potential of existing natural resources including biodiversity. This could include sustainably exploiting the potential of biodiversity to maintain standing forests while being socially inclusive (Nobre & Nobre, 2018). One such avenue is through a “bioeconomy,” in which natural resources are appropriated in such a way that maintains the integrity and autonomy of the resources, without following large-scale industrial systems in which the exploitation of natural resources is

supported by the control of production (Abramovay et al., 2021; Costa et al., 2021). In this case, strategies that reduce poverty could even represent an effective method for reducing deforestation, combining forest conservation with social well-being (da Silva Medina et al., 2022; Miyamoto, 2020).

The recent outbreak of war in Ukraine highlights the impacts of relying on globalized-agricultural markets and reinforces the need for alternative development pathways. Despite clearing forest areas larger than many of the world’s nations, a dependence on global agricultural supply chains can pose a risk to food security in Brazil. For example, president Jair Bolsonaro recently emphasized issues surrounding food security and was quoted in March 2022 as saying that if the war in Ukraine continues drastic measures could be required to address basic nutritional needs (Paraguassu, 2022). This preoccupation comes from intensive fertilizer inputs required by major crops such as soy that depend on imported potassium from Russia. Such preoccupations further reinforce the need for sustainable pathways to an Amazonian bioeconomy (Abramovay et al., 2021; Costa et al., 2021). For this to happen, Abramovay et al. (2021) highlighted four fundamental elements: “a) Recognition that, by ethical principles, strengthening the forest economy should support the improvement of local livelihoods; b) Institutional signaling against illegality and deforestation; c) Improvement in the quality of information about different products and their value chains; and d) Provoking the emergence of dynamic markets as alternatives to the incomplete, socially unfair, and imperfect markets that dominate the forest economy today”.

Adopting practices that avoid both deforestation and degradation could go hand-in-hand with strategies for poverty alleviation (Di Sacco et al., 2021). Forest loss in Amazonian agricultural frontiers continues to be subsidized by (1) land tenure regularization that incentivizes land-grabbing, (2) land reform programs, (3) rural credit that is decoupled from formal land ownership, (4) downgrading of environmental legislation and its effectiveness, and (5) amnesty for violations of illegal deforestation and incitements for noncompliance and the substitution between markets and actors which diminishes the effectiveness of regulations. (Azevedo-Ramos & Moutinho, 2018; Boucher & Chi, 2018; Ferrante & Fearnside, 2019; Garrett et al., 2021; Guimarães de Araújo, 2020; le Polain de Waroux et al., 2019; Pereira et al., 2020; Rajão et al., 2020). In addition to forest loss, forest degradation is an increasing challenge (Bullock et al., 2020). Regeneration and restoration can simultaneously counteract degradation, reduce greenhouse gas emissions, and improve local climates and ecosystem resilience (Rajão et al., 2020). Yet, such active management adds additional time and costs, which can be disproportionately prohibitive for small scale farmers who may become even more indebted without appropriate investments such as interest free loans and capacity building (Gil et al., 2016).

A potential caveat to our findings is that our analysis specifically focuses on the direct associations between forest loss and socioeconomic indicators. We did not assess effects through and/or across production chains that can, directly and indirectly, contribute to the variation in economic indicators (e.g., GDP) across the municipalities. Such effects are however likely to be secondary/marginal considering the temporal and spatial scale of our analysis. The broad agreement between our findings and previous studies also suggests that the patterns are a fair and unbiased reflection of forest cover changes and their associations across 5 Mkm². Additionally, the division of cover classes and subset identification was driven largely by the sample size of municipalities with different proportions of natural forest cover. Based on the temporal and spatial scale of our analysis we assume the trends found will be robust to potential uncertainty associated with the criteria used to select a representative subset of municipalities. There is potential for future studies to adopt techniques such as statistical matching and panel regressions (Schleicher et al., 2020) that may provide additional insight for comparisons among municipalities. Such studies could also include a broader range of socioeconomic variables that can help to provide a more detailed assessment of local scale patterns to identify what is driving socioeconomic development and maldevelopment across Brazilian Amazonia.

Implications for conservation

Our findings support evidence from across the tropics that show deforestation may be a short-term boon for agricultural

economies but does not necessarily generate transformative and equitable production systems or poverty alleviation. Poverty alleviation could be achieved across Brazilian Amazonia without forest loss through measures that directly improve sanitation and education, facilitate greater access to resources, and create opportunities to take advantage of available technologies and policies.

Methods

Data sources

We compiled the most up to date data from publicly available sources (Table 1) to test two predictions embedded in an implied direct cause-effect relationship between forest cover and poverty among municipalities from nine Brazilian states (Amapá, Amazonas, Acre, Maranhão, Mato Grosso, Pará, Tocantins, Rondônia, and Roraima). The results presented come from 794 of the 808 municipalities with economic data available in 2019 (IBGE, 2021). State capital municipalities were not included in any of the analyses as these represent distinct socioeconomic development trajectories within and between States and are unlikely to be representative of changes due to forest loss. Although the capital municipalities include a major proportion of the state population (IBGE, 2021), they were not included as we were interested in the direct relationships between forest cover and economic indicators not a quantification of consumption chain pathways. Municipalities whose geographic borders changed from 2002 to 2019 were also excluded.

Spatial data including municipality location and size were obtained from the Brazilian Institute of Geography and Statistics (IBGE) available at <https://www.ibge.gov.br/geociencias/downloads-geociencias.html>.

Forest loss

We used recent forest loss (cumulative sum of loss from the previous five years) to compare changes among municipalities. This five-year timespan was chosen based on strong correlations that prevented the inclusion of different forest loss timespans in the same model (Pearson correlations >0.87 among two to five-year timespans, Supplemental Material S1) and cross-correlation analysis of the temporal association between economic measures and forest loss (Supplemental Material S4). As the pair-wise correlations were so strong (Supplemental Material S1), here we assume that results at the scale of our analysis will be consistent across the range of lag values. The five-year period used in our study follows the timescale adopted by a previous study linking deforestation and cattle pasture expansion (zu Ermgassen et al., 2020). Forest loss was quantified using data derived from freely available annual land use and land cover data from 1985 to 2020 (MapBiomass 2021). The Brazilian Annual Land Use and Land Cover Mapping Project (MapBiomass) is a

Table 1. Annual Data for Municipalities Across Brazilian Amazonia.

Variable	Source	Years	Expected relationship if predictions are true
Forest loss			
Forest cover and loss	MapBiomias (2021)	1985–2019	
Economic indicators			
GDP and GVA for municipalities (standardized currency values)	IBGE (2021)	2002–2019	Positive association with increasing forest loss.
Average salary	IBGE (2019a)	2006–2019	Positive association with increasing forest loss.
Socioeconomic indicator			
Sanitation plan	IBGE (2019b)	2019	Positive association with increasing forest loss.
Internet connectivity	IBGE (2019b)	2019	Positive association with increasing forest loss.

collaboration between scientists that started in 2015. Remote sensing techniques are used to calculate a variety of land cover and land use data obtained from Landsat images (30 × 30 m resolution); with the raster data processed into different products that are freely available (Souza et al., 2020). Annual values of forest loss per municipality were obtained from pre-calculated summaries of the areas where a transition occurred from natural forest (including savanna and forest formations) to anthropic cover (MapBiomias Collection 6, available from <https://mapbiomas.org/en/statistics>, (MapBiomias 2021)). As the focus was on broad scale changes among municipalities, forest loss was expressed as the total summed forest area per municipality (including natural savanna and forest formations) that was converted to human land use each year.

Economic indicators

To compare economic indicators, we used annual municipality level data compiled and maintained by the IBGE (IBGE, 2021). There is a two-year delay between the collection and publication of the official Brazilian national accounts and the most recent municipality level economic data available was from 2019 (released on 17 December 2021) and does not, therefore, include any changes due to the COVID-19 pandemic. Three economic response variables were Gross Domestic Product (GDP) per capita, agriculture Gross Value Added (GVA) per capita, and average salary per municipality. These three indicators were chosen to represent distinct components of economic growth across the study area. GDP is the sum of all goods and services and agriculture GVA is the contribution of the agricultural sector to GDP (Kauano et al., 2020; Lipscomb & Prabakaran, 2020; Nobre et al., 2016). As agriculture is the main driver of forest loss across Brazilian Amazonia (Faria & Almeida, 2016; Garrett et al., 2021), we also included agriculture GVA per capita as the economic returns from forest loss would be expected to be stronger and sooner reflected in agriculture GVA than in GDP. Resident population, agriculture GVA, and GDP from 2002 to 2019 were used to calculate agriculture GVA per capita and GDP per capita. All final currency values were standardized (e.g., corrected for inflation) as part of the IBGE data compilation process and are directly comparable among years

from 2002 to 2019. The average salary per municipality was used to more closely represent the economic situation of the population from 2006 to 2019. The average salary was expressed as a proportion of the national minimum salary, thereby representing the purchasing power of workers within each municipality. The national minimum salary is updated annually by the Brazilian Federal Government using a calculation including the previous year's inflation and GDP. Although this national minimum salary does not directly represent the population living subsistence livelihoods and/or with informal employment, we include it as it is likely to represent a best-case indicator of income among municipality populations.

Socioeconomic indicators

In addition to economic indicators, we also compared forest cover/loss with two socioeconomic indicators: the existence of a sanitation plan and internet connectivity. Care must be taken to represent poverty and the context of the use of this word. Poverty has complex definitions and forms of measurement that differ with context and usage. Here, we consider poverty to be a state or condition in which a person or community lacks the resources and essentials for a minimum standard of living (well-being). The choice of two socioeconomic indicators followed principles laid out by frameworks such as the Sustainable Livelihood Approach (Scoones, 1998) and was based on available annual data and the scale and context of the study objectives. These two variables were selected as they are proxies for a broad range of basic indicators, are necessary to enable future socioeconomic development, and were also likely to change over the 18-year study period (2002 to 2019). The existence of a municipality sanitation plan was used to broadly represent sanitation and health conditions. Internet connectivity was included as a proxy for infrastructure, access, and opportunity. An approved sanitation plan is a fundamental step necessary for investment and improvements in sanitation and health care within municipalities. Internet is widely used across Brazil and many of the national level administration systems (e.g., taxes, loans, benefits, entrance to public universities, and banks) are accessed solely or

predominantly via online systems. Internet access was represented by the connectivity in 2019 among the government administrative offices/centers in each municipality. This was included as complete connectivity between administrative centers was likely to represent a best-case scenario for internet availability and coverage for the local populations in each municipality.

Subset identification and selection of comparable municipalities.

A subset from the 794 municipalities was selected to help isolate the effects of forest cover change and control variation caused by characteristics that could confoundingly influence the economic indicators. We did not follow the binning previously adopted by [Rodrigues et al. \(2009\)](#), rather we first established clearly separate cover class groups. Municipalities were first grouped based on the proportion of natural forest cover in 1986. As there could be annual variation in satellite image quality a median of natural forest cover from 1985, 1986, and 1987 was used (forest cover 1986 hereafter). A threshold of less than 40% for a “low” forest cover class was chosen as there were very few municipalities with both less than 30% forest cover and less than 50% indigenous area in 1986 ($n = 16$). Municipalities with high (at least 50%) indigenous area cover were not included, as due to profound cultural, social, administrative, and legal differences these areas are likely to experience distinct development trajectories in comparison to those with no or little indigenous area cover.

To include the same gradient range (0 to 40%), a forest cover range of 60–100% was chosen to represent

municipalities with more forest, thereby excluding intermediate cover values and generating clearly distinguishable “less” and “more” cover class groups. The more forest group (municipalities with more than 60% natural forest cover and less than 50% indigenous area) was further separated into municipalities that still retained at least 60% natural forest cover in 2019 (“high cover”) and those with less than 50% natural forest cover in 2019 (“medium cover”). This 50% value is below both the “half-world” threshold necessary for biodiversity conservation ([Dinerstein et al., 2017](#); [Leite-Filho et al., 2021](#)) and the 60% value estimated with the planetary boundaries framework as the minimum natural tropical forest cover necessary to stay within Earth’s “safe operating space” ([Steffen et al., 2015](#)). Cover in 2019 was obtained from the median of values from 2018, 2019, and 2020 (2019 hereafter).

To provide a valid comparison of differences due to forest cover change, the distribution of values for key socioeconomic proxy variables from the low forest class was used to select the subset of the other two classes. The low forest cover class was used as a reference class, with the variable values of this reference class used to select municipalities with medium and high forest cover that were otherwise broadly comparable in terms of socioeconomic characteristics from 2002 to 2019. The low forest cover class included municipalities from 7 states (Amapá, Amazonas, Maranhão, Mato Grosso, Pará, Roraima, and Tocantins). Municipalities were therefore only included from these seven states as different states have contrasting historic and present day development and administration patterns.

The key socioeconomic proxy variables were used to select a representative sample of municipalities with a similar central tendency (median) and range of values ([Table 2](#)).

Table 2. Socioeconomic Characteristics From the Selected Subset of Municipalities. This Cover Subset was Grouped Into Three Forest Cover Classes Using the Percent of Natural Forest Cover in 1986 as a Reference Level (“Low”: Less Than 40%, “Medium”: More Than 60% in 1986 but Less Than 50% in 2019 and “High” More Than 60% in 1986 and 2019).

	Low		Medium		high	
Subset description						
Number of municipalities	41		111		205	
Number of states	7		4		7	
Total municipality area (km ²)	89 K		243 K		557 K	
Urban concentration (total yes:no)	1:40		2:109		3:202	
Gold mining processes	0		0		0	
Characteristics	Median	Range	Median	Range	Median	Range
Forest cover 1986	32.9	(4.8–39.6)	70.5	(60.2–92.7)	85.8	(60.6–99.5)
Forest cover 2019	21.7	(4.7–39.1)	38.9	(8.9–49.9)	74.7	(60.2–99.4)
Municipality size (km ²)	1288	(200–12535)	1392	(150–11355)	1632	(159–12274)
Distance to state capital (km)	211	(44.1–753)	269	(40.9–735)	215	(19.4–741)
Population density	7.7	(0.2–150)	13.2	(0.8–103)	9.1	(0.4–88.7)
Industry Gross Added Value	5.0	(1.6–41.5)	4.9	(2.0–36.0)	4.7	(1.3–41.5)
Indigenous lands	0	(0–21.1)	0	(0–17.0)	0	(0–17.8)

- Municipality size: Size can, directly and indirectly, affect development through issues such as logistics, diversity of habitats, and natural resources.
- Distance to the state capital: Municipalities closer to state capitals are likely to have improved infrastructure, logistics, and market access.
- Industrial activities contribute strongly to economic development across Brazilian Amazonia. This sector includes mining, electricity generation (e.g., hydro-power), and construction. The contribution of the industrial sector was expressed as the % of the total Gross Value Added per year per municipality.
- Population density is a proxy for the needs and consumption of the population.

Pair-wise comparisons also showed that the distribution of socioeconomic variable values was similar among forest cover classes (Kolmogorov–Smirnov $P > 0.05$ for all pair-wise comparisons except for forest cover percentages, Figure 5).

Analysis

All analysis was run with original Brazilian currency values. Currency values were converted to US\$ in text, figures, and tables to facilitate comparison with previous studies (2019 rate of US\$1 to R\$3.946).

Generalized Additive Models (GAMs) were used to establish evidence of associations between forest loss and economic indicators. GAMs are a powerful and flexible modeling technique (Pedersen et al., 2019; van Rij et al., 2019) that were chosen to develop models for testing the two predictions with the available data, as the responses representing economic indicators could be explained using generalized additive mixed effect models with a combination of parametric, non-parametric (smoothed non-linear), and random terms (Pedersen et al., 2019; van Rij et al., 2019; Wood, 2006; Wood, 2020). This approach provides a systematic description of the patterns in the data rather than focusing solely on the statistical significance of the differences between the response and explanatory variables (Pedersen et al., 2019; van Rij et al., 2019). An iterative model checking process was adopted to ensure that numerically stable model fits and robust inference were possible (Wood, 2006; Zuur et al., 2010), copies of the data and code used are available from <https://doi.org/10.5281/zenodo.6536826>.

All models were run with the Tweedie error family (Dunn, 2017; Tweedie, 1984) and estimated using restricted maximum likelihood (REML, (Pedersen et al., 2019; Wood, 2006)). The three economic indicator responses were modeled with annual forest loss (the cumulative sum of loss from the previous five years) expressed in km² and as % of the 1986 forest cover in each municipality (Supplemental Material S2 for model specifications and results). Spatial relationships were included using geographic coordinates of

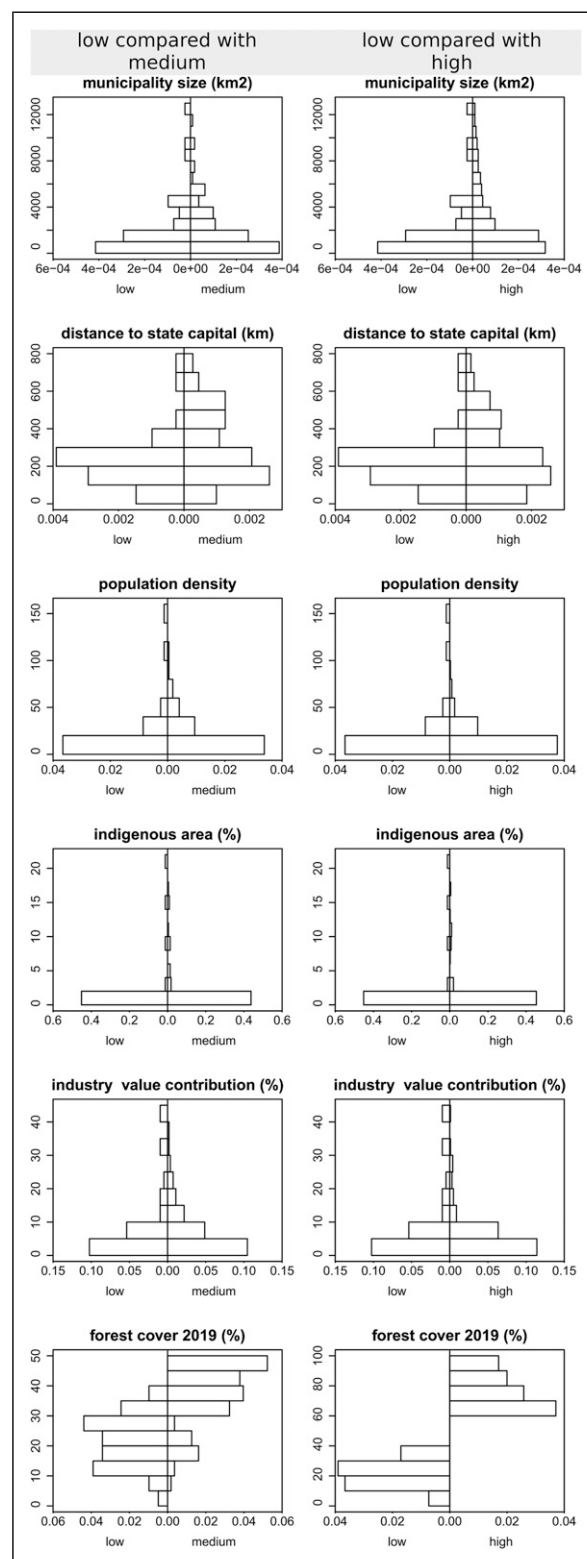


Figure 5. Distribution of socioeconomic proxy variable values across municipalities grouped into three forest cover classes. Subset grouped into three forest cover classes using percent of natural forest cover in 1986 as a reference level (“low”: less than 40%, “medium”: more than 60% in 1986 but less than 50% in 2019 and “high” more than 60% in 1986 and 2019).

the Mayors' office (administrative center) of each municipality. The Euclidian distance (km) from each municipality to the state capital was calculated between the coordinates of the respective Mayors' offices. Temporal relationships were modeled by including year as a smoothed explanatory variable and an AR1 process for residual correlation matrix (autoregressive correlation structure). To test if the different cover classes in the selected subset of municipalities explained variation in the three economic indicators, cover class was included as a categorical factor in the GAMs instead of annual forest loss (Supplemental Material S3 for model specifications and results). All models were checked for spatial autocorrelation via semivariograms of model residuals and for temporal autocorrelation via autocorrelation plots of model residuals (Wood, 2006; Zuur et al., 2010).

Acknowledgments

We would like to thank Willie Shubert for useful discussions that helped to develop the text. We are grateful to Mairon Bastos Lima, a reviewer, and the Associate Editor for their constructive comments on earlier versions of the text.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

Data Availability

The data that supports the findings of this study are available in the supplementary information of this article. A copy of the data and code is also available at <https://doi.org/10.5281/zenodo.6536826>.

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Supplemental Material

Supplemental material for this article is available online.

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