Title: Land use change models that integrate quantitative and qualitative approaches better explain deforestation patterns in Amazonian protected areas

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Abstract

Agricultural frontiers in the Amazon Basin – many of which overlap with protected areas – experience rapid forest conversion to agriculture and pasture, threatening ecological health and globally significant ecosystem services. Effective responses to protected area deforestation require understanding the socio-environmental factors that increase the likelihood of forest conversion, which may be common region-wide or specific to each protected area. Crucially, standard, quantitative approaches to land use change modeling may not include some of these factors, constraining our understanding of and response to deforestation. Dominant discourses about deforestation – promoted by government actors and conservation organizations – also shape responses to deforestation. We integrate quantitative and qualitative analysis of deforestation dynamics into land use change models of three protected area complexes in the Amazon to understand region-wide and site-level factors related to deforestation and the ability of conservation discourses to explain deforestation patterns. Our integrative methodology yielded better model performance than standard land use change modeling for all sites. From 2008-2018, forests on steeper slopes with lower population densities were less likely to experience deforestation, while forests surrounded by non-forest pixels and located closer to agriculture and fire activity were more likely to convert. Finally, while dominant discourses sometimes aligned with the results of integrated models (e.g., fires were associated with increased deforestation probability in all sites), our models did not support some factors commonly cited in deforestation discourses (e.g., REDD+ concessions had no relationship with deforestation in Peru's Tambopata National Reserve and Bahuaja-Sonene National Park). Our results can inform management responses to stem deforestation (in our study sites and across the Amazon) and emphasize the need for a balanced, integrative approach to operationalizing dominant discourses in conservation science and practice, as the framing of deforestation – through quantitative and qualitative approaches – shapes understandings of and responses to deforestation.

Introduction

Forest conversion to agriculture occurs along agricultural frontiers throughout the Amazon Basin, with consequences for Indigenous communities, biodiversity, and ecosystem services [1–3]. Agricultural frontiers are remote, sparsely settled areas with active land use conversion for agriculture or livestock production [4,5]. While some policy interventions have successfully reduced forest clearing in the Amazon [6,7], increasingly in the Amazon and around the world, areas of current and potential agricultural expansion overlap with areas of conservation priority, including protected areas [8,9].

Protected areas are a leading tool for reducing forest loss worldwide, and by 2022, protected areas covered 25% of the Amazon region [10], with an additional ~16% of land area in the nine countries that comprise the Amazon under some form of area-based conservation [11]. These protected areas have had varying impacts on deforestation. Amazonian protected areas are diverse in their governance and the degree to which extractive activities are permitted, with consequences for forest cover [12–15]. Notably, despite the reductions in deforestation within protected areas relative to unprotected forest in the Amazon Basin, forest loss continues even within protected area boundaries [16], a trend mirrored worldwide [17].

The precise land use change pathways of agricultural frontiers vary with local environmental, socioeconomic, and policy contexts [7,18]. To understand deforestation dynamics in a particular place therefore requires understanding the spatial variation in socio-environmental drivers of forest conversion and variation in the strength of their effect on land use and land cover [19,20]. Previous studies have compared deforestation trends and drivers, often using countries as the scale of analysis [7,21] or comparing individual sites within a country [22]. Across the Amazon, these analyses have identified common drivers of deforestation such as proximity to roads or navigable rivers [7,23]. Other factors have emerged at smaller spatial scales, such as oil palm expansion in Peru [24] and oil exploration in the western Amazon [25]. Despite regional- and national-level commonalities, the specific context of each individual protected area also plays a role in determining the factors that contribute to land use change within and around its boundaries, highlighting the importance of site-level land use change analyses [7]. Understanding the context-specific factors driving deforestation is important because it dictates effective solutions.

We use an integrative mixed methods approach to compare factors related to increased forest conversion to agriculture in three case study sites across the Amazon Basin. Our novel approach effectively identifies and integrates varied, context-specific factors into land use change modeling through an iterative approach to integrating quantitative and qualitative data [26] that draws on remote sensing and qualitative discourse analysis. Previous work demonstrated that models that integrate variables from both qualitative and quantitative approaches have the best ability to predict deforestation in a protected area in the Brazilian Amazon [27]. Here, we broaden this approach to test whether this finding holds across multiple protected area complexes in the Amazon Basin. Further, we explicitly compare the relative importance of different factors related to forest conversion to agriculture across three protected area complexes with different geographic, socioeconomic, and political contexts.

Methods

Study sites

We modeled land use change in three protected area complexes in the Amazon Basin: Brazil's Jamanxim National Forest, Bolivia's Amboró and Carrasco National Parks, and Peru's Tambopata National Reserve and Bahuaja-Sonene National Park (**Figure 1a**). The Jamanxim National Forest case study consists of a single protected area, while the other case studies consist of two or more adjacent protected areas (**Figure 1b**). These sites represent protected area complexes with similar sizes (12,962-13,661 km^2) and relatively high rates of deforestation, but they have varying deforestation dynamics and drivers [28–32].

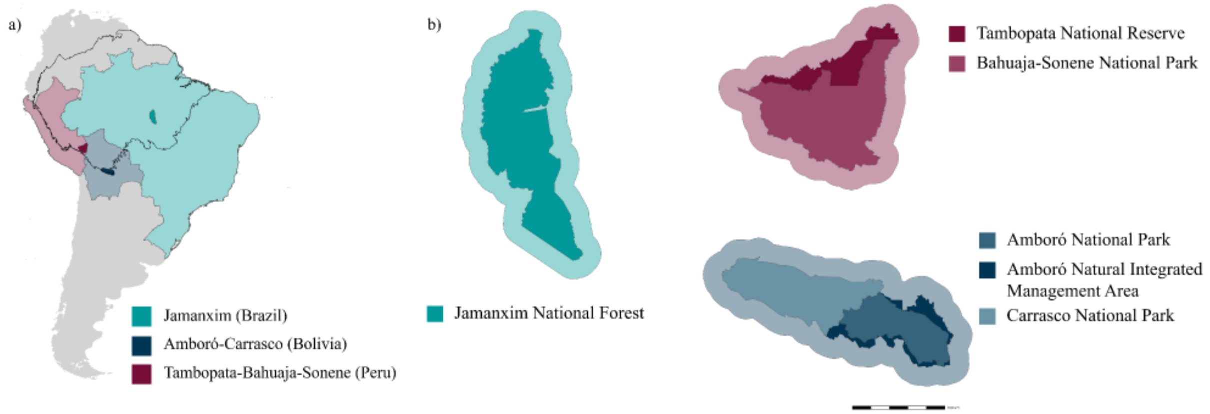

Figure 1. Map of the three case study sites. a) Location of the three case study sites within the Amazon Basin (black outline). b) Detailed map of the protected area complexes comprising each case study site, with a 20-kilometer buffer surrounding the protected area boundaries.

Jamanxim National Forest, in Pará, Brazil, was established in 2006 to address deforestation related to highway development. While it is managed for sustainable use objectives [33], the national forest has experienced deforestation through land-clearing for ranching, agriculture, and land speculation [34–36].

Amboró National Park (established in 1984), Carrasco National Park (1991), and Amboró Natural Integrated Management Area (1995) (hereafter "Amboró-Carrasco") have experienced deforestation primarily for small-scale agriculture and ranching [37–39]. Amboró-Carrasco also faces pressure from coca cultivation, hydrocarbon extraction, and a proposed hydropower dam [39,40].

Tambopata National Reserve (established in 2000) and Bahuaja-Sonene National Park (1996) are in the Madre de Dios and Puno departments of Peru, a globally recognized biodiversity hotspot [41]. The two parks (hereafter "Tambopata-Bahuaja-Sonene") were created through a participatory process facilitated by the non-governmental organization Conservation International [42]. Tambopata has a buffer zone with land use restrictions along its northern border [43]. Prior to the mid-2000s, agricultural expansion drove forest loss in the region, but informal gold mining became a major factor beginning around 2006 [44,45].

For all case study sites, we modeled land use change within the protected areas and in 10- and 20-kilometer buffers around the protected areas, to capture land use change dynamics directly outside the protected areas [46–48]. In the case of Tambopata-Bahuaja-Sonene, the buffer extended over the border between Peru and Bolivia. We cropped the buffer to only include the portion within Peru because the sociopolitical factors identified in the discourse analysis vary by nation [49]. We modeled deforestation from 2008 to 2018, ending our analysis before the beginning of Jair Bolsonaro's presidency in Brazil because his administration had a large impact on deforestation rates and conservation discourses [50,51].

Land use change maps

Our land use change models used published land cover maps from 2008 and 2018 for each case study site [32]. These maps were generated through supervised classification of cloud-free composites using pixels from Landsat 5 (TM), Landsat 7 (ETM+), and Landsat 8 (OLI) Surface Reflectance datasets with 30 m resolution, using random forests. The maps identify forest, agricultural land and pastures, bare soil, built areas, wetlands, water, and in Amboró-Carrasco, deserts, with an overall accuracy rate of > 90% across the case study sites [32]. The maps indicated forest loss from 2008 to 2018 of 471 km^2 in Jamanxim, 187 km^2 in Amboró-Carrasco, and 63.6 km^2 in Tambopata-Bahuaja-Sonene.

Land use change modeling and projection

We used logistic regression to model the probability of conversion to agriculture for each forested pixel from 2008-2018, extracting pixel values along a 300-meter grid to avoid introducing spatial autocorrelation [27]. We performed all modeling in R [52]. Following a methodological framework detailed in Siegel et al. (2022), we created models for each site using different combinations of variables derived from an iterative process for integrating qualitative and quantitative methods. We selected variables using 1) a review of land use change papers in the Amazon Basin (Supplementary Materials), and 2) a qualitative discourse analysis of textual material addressing the causes of and solutions to forest conversion ([27]; Supplementary Materials). The discourse analysis identified deforestation discourses promoted by government and conservation actors: we coded management, policy, and advocacy documents, as well as gray literature at the park-, state-, and national-scale at the three case study sites, using snowball sampling, legislative databases, and non-governmental organization (NGO) websites in English, Spanish, and Portuguese (**Table S1**). We coded all documents in NVivo 12 [53], first using a set of predetermined themes identified from our literature review of variables used in Amazon land use change models, and then adding emergent themes that arose through the coding process, as described in Siegel et al. (2022) (**Table S2**).

For each case study site, we built four models. The first used solely variables from the review of Amazonian land use change literature (the LUC model), the second only used variables identified through discourse analysis (the DA model), the third model that included all variables used in the LUC model and the DA model (the LUC and DA model), and the fourth model used the variables that emerged as statistically significant in the LUC model and qualitatively important through the discourse analysis (refined LUC and DA model) (**Figure 2**). The variables for the LUC model were the same across all case study sites and related to topography, accessibility to infrastructure and markets, agricultural suitability, human population characteristics, management status, and neighborhood effects (the proportion of surrounding pixels that were forested) (**Table 1**). The DA model variables varied across study sites, depending on the themes identified through the discourse analysis (**Table 1**; **Table S3**). The models for Jamanxim differ from those in Siegel et al. (2022) due to minor changes in methodology to ensure comparability of the regression coefficients across case study sites. We compiled and standardized data from global, regional, and local datasets (**Table 1**), using the R packages *sf*, *raster,* and *lwgeom* [54–56]. To facilitate comparisons between study sites, we centered and scaled continuous variables.

While the variables for the LUC model were spatially explicit and quantitative or categorical and thus straightforward to include in our models, additional steps were required to translate the themes identified in the discourse analysis into quantitative, spatially explicit proxies. For each theme, we attempted to develop a quantitative, spatial proxy using available data and published literature [27,57]. As an illustration, sustainable development emerged as a theme mediating forest loss in Amboró-Carrasco and Tambopata-Bahuaja-Sonene, and we used distance to ecotourism sites and the presence of PES programs and REDD+ projects as proxies for this theme. Some themes did not translate into spatial, quantitative proxies with available data; we did not include these themes in our models but integrated them into our interpretation of model results.

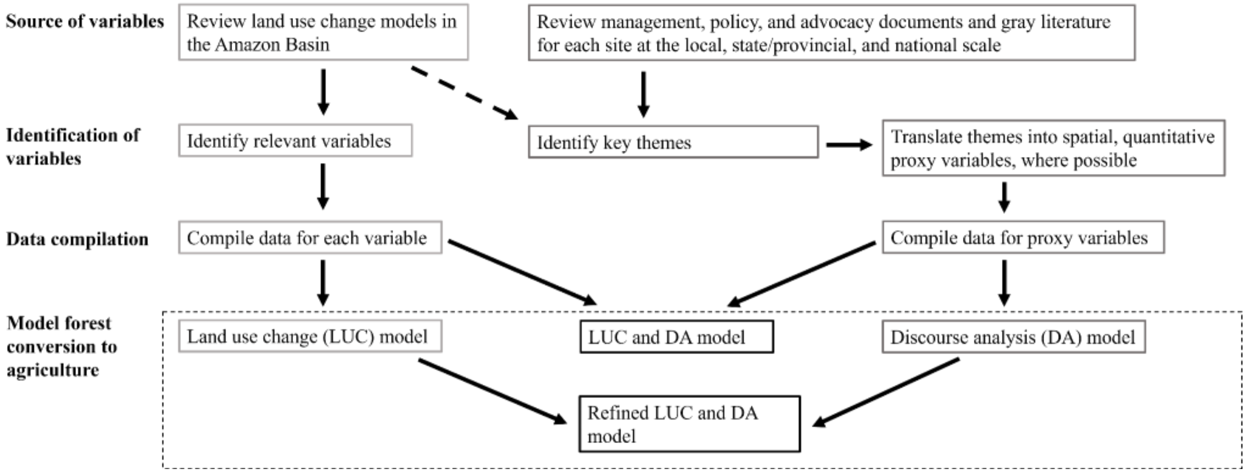

Figure 2. Overview of the methods used to identify and assemble the variables for the four logistic regression models created for each site: the land use change (LUC) model, the discourse analysis (DA) model, the LUC and DA model, and the refined LUC and DA model.

To avoid multicollinearity, we assessed correlations between continuous variables and the variance inflation factor (VIF), using a final suite of variables for each model that minimized VIF and collinearity. Each model thus had a subset of the potential variables. When faced with highly correlated explanatory variables, we selected which variable to keep in the model based on data quality and spatial resolution, the year of the data relative to our study period, and the expected strength of the variable's relationship to agricultural expansion [27]. **Table S3** lists the variables included in each final model. Due to the strong emphasis on unauthorized mining in the Tambopata-Bahuaja-Sonene discourses, we ran a version of the refined LUC & DA model for Tambopata-Bahuaja-Sonene that included distance to unauthorized mining sites as an explanatory variable, despite its collinearity with other variables (**Table S4**).

Table 1. Variables used in LUC models, including the LUC variables used for each case study site, and the site-specific DA variables, demonstrating the translation from qualitative theme to spatial and quantitative proxy variable.

LUC variables		
Variable	**Source**	**Case study sites(s)**
Elevation Slope Aspect	[58]	All
Distance to roads	[59]	
Distance to rivers	[60–63]	
Distance to mines and mining concessions	[64–66]	
Distance to cities	[67–70]	
Crop suitability	[71]	
Precipitation	[72]	
Soil moisture	[73]	
Population density	[68,69,74]	
Poverty rate	[75–77]	
Neighborhood effect	Derived from Kinnebrew et al. (2022)	
Management status	[78]	
DA variables		

Theme	**Proxy variable**	**Source**	**Case study site(s)**
Physical accessibility, agricultural and land-clearing activity	Distance to agriculture	Derived from Kinnebrew et al. (2022)	All
	Distance to fires	[79]	
	Fire density	[79]	
Resource extraction	Distance to unauthorized mines	[80]	All
Ranching	Head of cattle per km^2	[81,82]	Jamanxim, Amboró-Carrasco
Legal challenges to protected areas	PADDD	[83]	Jamanxim, Tambopata-Bahuaja-Sonene
Infrastructure development	Distance to proposed railroads	[84]	Jamanxim
	Distance to proposed dams	[85]	
Land tenure; settlements; land grabbing	Unallocated public land	[86]	Jamanxim
	Agricultural reform settlements	[87]	Jamanxim
	Land tenure	[88]	Amboró-Carrasco
	Distance to Indigenous communities	[89]	Tambopata-Bahuaja-Sonene
Sustainable development	Distance to tourism	[90,91]	Amboró-Carrasco, Tambopata-Bahuaja-Sonene
	Presence of PES programs	[92]	Amboró-Carrasco

	Presence of REDD+ concessions (medicinal plants, nut production, reforestation plots)	[93]	Tambopata-Bahuaja-Sonene
Enforcement capacity	Distance to control posts	[94]	Tambopata-Bahuaja-Sonene
Migration and settlement patterns	Location to the north or south of the geographic boundary from El Torno to Tablas Monte	Derived	Amboró-Carrasco

Model comparisons

We assessed model performance using Akaike information criterion (AIC) and analysis-of-variance (ANOVA) comparisons of model fit. To account for the different numbers of variables in the models, we used McFadden's adjusted pseudo R^2 to compare model performance for a given study site [95].

We compared the amount and location of deforestation for agriculture predicted in 2018 by the models for each site to the actual observations of forest conversion. We used each logistic regression model to create a landscape representing each pixel's predicted probability of forest conversion to agriculture in 2008. Using these predicted probability maps and Monte Carlo simulations, we made 1000 projected landscapes in 2018 for each model, assuming no change in land cover for pixels that were non-forest in 2008. We used the observed forest loss area for each site to determine forest loss in the projected landscape by allocating forest loss to the pixels that converted most frequently across the simulations until we reached the observed quantity of forest loss. This resulted in a single predicted 2018 landscape for each model. Comparing these predicted landscapes with the observed 2018 landscape in each site, we calculated quantity and allocation disagreement using the *diffeR* package [96,97]. These methods are described in more detail in Siegel et al. (2022).

Results

Comparisons of model performance

Across all sites, models that included variables from the discourse analysis along with standard land use change modeling variables explained the most variation in observed forest conversion to agriculture, as measured by McFadden's pseudo R^2 and AIC (**Table 2**). In Jamanxim, the refined LUC & DA model explained the most variation in forest conversion, explaining almost twice as much variation as the LUC model. In Amboró-Carrasco, the LUC & DA and refined LUC & DA models explained the most variation in forest conversion, followed by the DA model, then the LUC model, with less drop-off in variation explained than in Jamanxim. Per AIC, the refined LUC & DA model outperformed the LUC & DA model, but ANOVA analysis revealed no significant difference in performance between the two. In Tambopata-Bahuaja-Sonene, the LUC & DA model explained the most variation, followed closely by the refined LUC & DA model. The LUC model explained the least variation. Including distance to unauthorized mines did not yield significant improvements in model performance for Tambopata-Bahuaja-Sonene. The Tambopata-Bahuaja-Sonene models explained more variation than the other sites' models.

Table 2. Model performance metrics for the four models across the three case study sites. AIC values compare model performance within a given case study site.

Case study	Metric	LUC model	DA model	LUC & DA model	Refined LUC & DA model
Jamanxim	AIC	82567	66822	66044	62357
	McFadden's pseudo R^2 (%)	24.7	39.0	39.8	43.1
	Allocation disagreement	0	0	0	0
	Quantity disagreement	0.0256	0.0232	0.0226	0.0202
Amboró-Carrasco	AIC	62876	59373	56522	56506
	McFadden's pseudo R^2 (%)	31.1	34.9	38.1	38.1
	Allocation disagreement	0.0167	0.0001	0.0008	0.0113
	Quantity disagreement	0.0428	0.0511	0.0508	0.0456
Tambopata-Bahuaja-Sonene	AIC	2986	2538	2328	2331 (2329*)
	McFadden's pseudo R^2 (%)	41.2	49.9	54.4	54.3 (54.4*)
	Allocation disagreement	0.0011	0.0020	0.0012	0.0011 (0.0011*)
	Quantity disagreement	0.0049	0.0044	0.0049	0.0049 (0.0049*)

* Refined LUC & DA model when distance to unauthorized mines is included as a predictor variable

The different models' allocation (the amount of difference between the predicted and observed maps caused by spatial mismatch in the location of the pixels in each land cover class) and quantity (the difference in the proportion of pixels in each land cover category in the predicted and observed maps) disagreement was not as similar across the sites (**Table 2**). In Jamanxim, all models had negligible allocation disagreement, and the refined LUC & DA model had the lowest quantity disagreement. In Amboró-Carrasco, the DA model had the lowest allocation disagreement, but the LUC model had the lowest quantity disagreement. In Tambopata-Bahuaja-Sonene, the DA model had the highest allocation disagreement but the lowest quantity disagreement. The LUC model and refined LUC & DA models had the lowest allocation disagreement. Allocation disagreement was low across all sites, with the highest allocation disagreement in Amboró-Carrasco (mean of 0.007 across the four models). Quantity disagreement was similarly low in Tambopata-Bahuaja-Sonene (mean of 0.005) but higher in Jamanxim (mean of 0.023) and Amboró-Carrasco (mean of 0.048).

Site-level factors related to forest conversion to agriculture

Across all models in Jamanxim, forested sites on steeper slopes, at higher elevations, and further from agriculture, past fire perimeters, unauthorized mining, and proposed railroads had lower probability of converting to agriculture (**Tables S5-S8**). Forested sites with higher population densities also had lower conversion probability, while sites surrounded by a higher proportion of non-forest pixels were more likely to convert. Forested sites in the 10- and 20-km buffer outside Jamanxim National Forest were also more likely to convert to agriculture, as were sites in locations with greater fire densities and higher proportions of unallocated public land. Other variables' relationships with the likelihood of forest conversion varied across models.

In Amboró-Carrasco, forested sites located on steeper slopes, at higher elevations, more distant from roads, rivers, mining concessions, cities, agriculture, past fire perimeters, and unauthorized mining sites always had lower probabilities of converting to agriculture (**Tables S5-S8**), as did forests within parcels enrolled in PES programs. Forested sites with higher crop suitability and a higher proportion of non-forest neighboring pixels were more likely to convert, as were sites with higher fire density and formalized land tenure. Forests in the 10- and 20-km buffer outside the protected area complex were also more likely to convert. Across the models, distance to tourism and precipitation did not have significant relationships with forest conversion probability. As in Jamanxim, there were also variables whose relationship with deforestation probability varied across the models (e.g., population density and poverty rate).

Across the models in Tambopata-Bahuaja-Sonene, forests located further from agriculture and fires were less likely to convert, while forested sites with higher crop suitability, a higher proportion of non-forest neighboring pixels, higher fire density, and presence of PADDD proposals were more likely to convert. Distance to roads, cities, and unauthorized mining sites did not have significant relationships with forest conversion, and neither did the locations of REDD+ concessions. Other variables (e.g., elevation, distance to rivers, and distance to tourism sites and control posts) had differing relationships with deforestation, depending on the model.

Cross-site comparisons

To compare factors related to forest conversion across the three sites, we focus on the results of the LUC & DA model, as this was the best-performing model (with similar performance and variable relationships as the refined LUC & DA model). In all sites, the probability of forest conversion to agriculture from 2008-2018 increased as slope, population density, distance to agriculture, and distance to past fire perimeters decreased, and as fire density and the portion of non-forest surrounding pixels increased (**Figure 3, Table S7**). Put simply, forested areas with low human population density and flatter terrain, located closer to areas with higher fire activity and in proximity to existing agriculture or other non-forest land covers were more likely to convert. In Jamanxim and Amboró-Carrasco, forests located closer to roads and unauthorized mining sites had higher probability of conversion, while neither variable was included in the Tambopata-Bahuaja-Sonene model due to collinearity with other variables. When we ran a version of the refined LUC & DA model for Tambopata-Bahuaja-Sonene that intentionally included distance to unauthorized mining sites as an explanatory variable (in response to the high importance this variable received in the discourse analysis), it did not have a significant relationship with forest conversion probability (**Table S4**). The Supplementary Materials include tables with the coefficient estimates from all four models across all three sites (**Appendix 3, Tables S5-S8**).

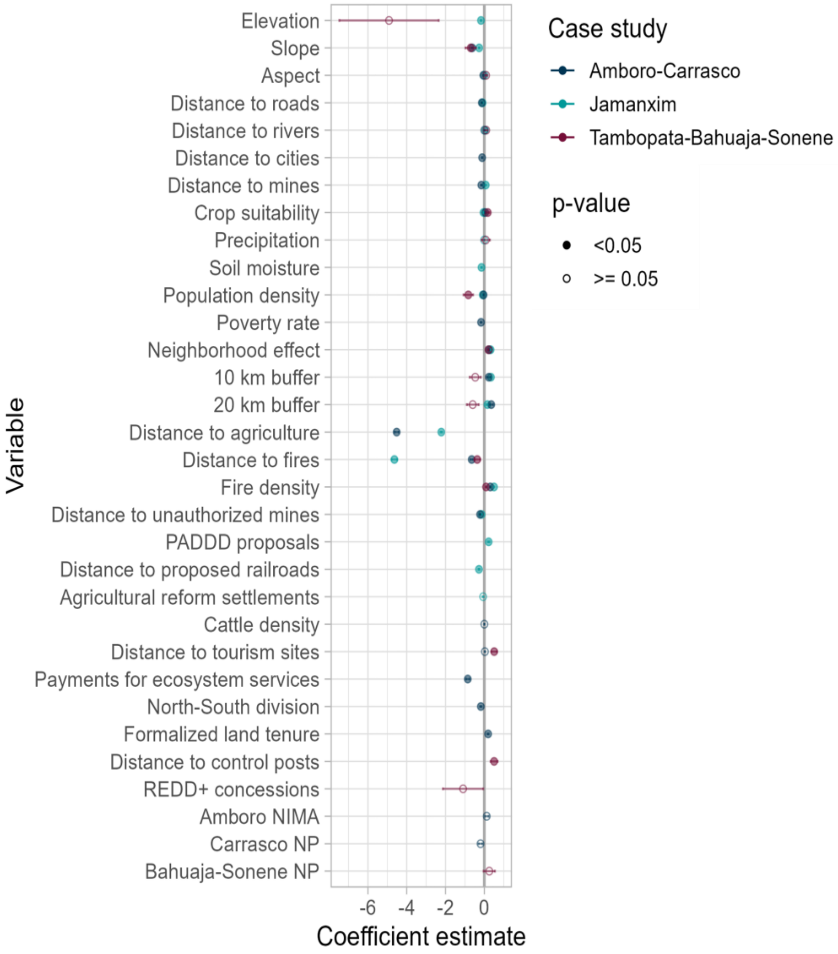

Figure 3. Coefficient estimates for the explanatory variables included in the LUC & DA model for the three sites, with their standard errors. All variables were scaled and centered. The coefficient estimate for distance to agriculture in Tambopata-Bahuaja-Sonene (β = -81.3137 ± 7.9017, $p < 0.001$) is omitted for ease of visualization. Filled circles indicate statistically significant estimates ($p < 0.05$), while empty circles represent estimates with p-values ≥ 0.05. All coefficient estimate values reported in Table S7.

The remaining variables had inconsistent relationships with the likelihood of forest conversion across the three sites. For example, in Jamanxim, forests closer to rivers had higher conversion probability, but the relationship was not significant in the other sites. In Jamanxim, forested points located further from mining sites were also more likely to experience conversion, while the opposite pattern held for Amboró-Carrasco, and distance to mines was not included for Tambopata-Bahuaja-Sonene due to collinearity with other variables. In Amboró-Carrasco and Tambopata-Bahuaja-Sonene, sites with higher crop suitability had increased probability of forest conversion, but this relationship was reversed in Jamanxim, where there is much less spatial variation in crop suitability. And while forested points located in the 10- or 20-km buffer outside of the protected areas in Jamanxim and Amboró-Carrasco were more likely to convert than forested points located within protected area boundaries, no such relationship existed for Tambopata-Bahuaja-Sonene.

Some variables were only included in the model for a single site – due to lack of relative importance in the discourse analysis or collinearity with other variables – preventing cross-site comparisons. In Jamanxim, as soil moisture and distance from proposed railroads increased, probability of forest conversion decreased, while the presence of PADDD proposals was related to higher probability of conversion. In Amboró-Carrasco, distance to cities, poverty rate, geographic location in the southern half of the study site, and enrollment in PES had negative relationships with forest conversion, while formalized land tenure was associated with increased conversion. Forests in Carrasco National Park had lower conversion probability than those in Amboró National Park. In Tambopata-Bahuaja-Sonene, sites located further from control posts had higher conversion likelihood.

Discussion

Our findings emphasize the limitations of large-scale and global modeling for understanding deforestation dynamics, as our models using only standard land use change variables had the poorest performance and missed context-specific factors, constraining the potential for tailored conservation responses. In contrast, models that integrated data and methods from qualitative and quantitative approaches best predicted forest conversion to agriculture across all sites, expanding on previous findings [27] and highlighting the benefits of integrative methodologies for conservation science [26].

Analysis of conservation discourses identified significant regional and site-specific factors. Discourses across all sites stressed the role of fires in facilitating the spread of deforestation across agricultural frontiers. In our models, we found that proximity to existing agriculture and past fire locations, and high density of past fires, were associated with increased likelihood of forest conversion, supporting dominant conservation discourses. The discourse analysis also identified PES programs and migration and settlement patterns as important factors in Amboró-Carrasco, proposed infrastructure and PADDD events in Jamanxim, and tourism and enforcement in Tambopata-Bahuaja-Sonene, and our models quantitatively supported these qualitative findings.

Our identification of common factors related to deforestation can inform conservation interventions in protected areas across the Amazon Basin. While we cannot assume that the patterns observed in our case study sites hold uniformly across the region, the common trends across three sites with diverse geographies and social, economic, and political contexts suggests that these factors – slope, proximity to existing agricultural land and other non-forest land uses, and fire activity – may be important in other locations as well. However, some variables that are commonly included in land use change models for the Amazon did not have the same relationships with deforestation probability across the three sites, again illustrating the limitations of large- and global-scale analysis.

Our findings also demonstrate the potential for dominant conservation discourses to constrain our understanding of the drivers of and solutions to deforestation in protected areas. The site-specific variables identified through the discourse analysis were not always quantitatively supported by our models. For example, in Amboró-Carrasco, the discourse analysis indicated that poverty was a driver of deforestation, but our models found the opposite relationship: higher poverty rates correlated to lower forest conversion (**Figure 3**). Conservation discourses associating the rural poor with deforestation are persistent and prevalent in the Amazon and beyond [98–100], even when data do not support these claims [101]. These discourses have shaped past policy responses, with ineffective and unethical outcomes [102]. Thus, while conservation discourses provide a window into potentially important factors related to deforestation in protected areas, they may also reproduce power dynamics and recycle old tropes. We thus suggest that while qualitative methods and data can enrich land use change modeling – and thus deepen our understanding of the drivers of and potential solutions to deforestation – quantitative modeling can in turn illuminate conservation discourses' oversights.

There were additional, qualitatively significant themes that we identified through the discourse analysis that we were unable to integrate into our quantitative models. In some cases, this was due to lack of spatial variation in the themes over the area of an individual site (e.g., agricultural policies, which apply at coarser spatial scales). Other themes lacked spatial, quantitative proxies with available data, as was the case for "level of local participation and inclusion" in Amboró-Carrasco and "lack of commodity traceability" in Jamanxim (**Table S2**). In addition, there were scale mismatches for some variables in our models (e.g., cattle density, poverty rate, and population density were available at the municipal level, so the relationships between those variables and the likelihood of forest conversion may reflect municipal-level confounding variables).

While our integrated models supported many of the relationships between explanatory variables and deforestation that would be predicted given existing literature and conservation discourses [22,23,103], we observed some unexpected relationships. In all sites, higher population densities were associated with lower forest conversion probability; this may reflect the underlying data's coarse spatial scale. In Amboró-Carrasco, areas with formalized land tenure had increased deforestation probabilities, reflecting the mixed evidence about the link between formalized land tenure and deforestation globally [104]: land tenure protects against encroachment and appropriation, but rights holders may not choose land uses that align with conservation priorities [105]. In Jamanxim, forests located further from rivers and mining concessions had increased conversion probabilities, and neither proportion of unallocated public land nor presence of agricultural reform settlements had a significant relationship with forest conversion probability, contrary to our expectations [106,107]. Finally, in Tambopata-Bahuaja-Sonene, forests located within the protected areas or in REDD+ concessions did not have reduced deforestation probabilities relative to unprotected or non-concession forests. Distance to unauthorized mines was also not a significant explanatory variable, despite a strong emphasis on this dynamic in the discourse and published literature on deforestation in the region [44,108–110].

Conclusions

Through integration of qualitative analysis of conservation discourses with quantitative land use change modeling, we identified factors related to deforestation in three protected areas in Amazonian agricultural frontiers. We found that integrated land use change models better explained patterns of forest conversion to agriculture from 2008-2018 across a diverse region, highlighting the potential for conservation discourses to inform land use change modeling and potential limitations of modeling at large spatial scales. Simultaneously, our results emphasize the need to critically consider dominant conservation discourses, as they may reflect the priorities of powerful actors rather than on-the-ground dynamics.

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Supplementary materials

Appendix S1: Land use change literature in the Amazon
Appendix S2: Discourse analysis methods
Appendix S3: Models of land use change in the three case study sites

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Supplementary Materials

Contents

Appendix S1: Land use change literature in the Amazon

To identify 1) variables commonly used for land use change models in the Amazon and 2) our initial themes for the discourse analysis, we conducted a literature review of papers published through the year 2020. We assembled the variables used for our land use models based on consensus variables in these publications. The majority of the papers focused on land use change in the Amazon region [1–11], while others had a pan-tropical focus [12] or examined forest conversion in specific tropical forests outside of the Amazon Basin [13].

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Appendix S2: Discourse analysis methods

Here we provide further description of the discourse analysis methods, complementing the details provided in the Methods section of the main text and drawing from the methods described in Siegel et al. 2022 – the text below is adapted from Siegel et al. 2022 [1]. We sampled to the point of saturation.

We selected documents for inclusion in the discourse analysis using a systematic online search. To be included, documents had to mention the name of the case study protected area(s) (i.e., Jamanxim National Forest, Tambopata National Reserve, Bahuaja-Sonene National Park, Amboró National Park, Carrasco National Park, Amboró Integrated Management Natural Area) or the province(s) or department(s) where they are located (i.e., Pará, Madre de Dios, Puno, Santa Cruz, Cochabamba). The documents also had to include the terms "deforestation," "agricultural development," or "agricultural expansion" in English, Spanish, or Portuguese.

We assembled four categories of documents: management, policy, gray literature, and advocacy. Management documents largely consisted of protected area management plans, while policy documents included laws and decrees related to protected areas, forest management, and agricultural expansion). We defined gray literature as reports written by government agencies or non-governmental and civil society organizations (NGOs). We created a separate category of advocacy documents that included articles and other documents written by NGOs or other civil society actors to promote their campaigns and initiatives or to support specific arguments.

We included policy documents that encompassed either the protected area(s) or the related province/department, compiling all laws, decrees, institutional regulations, etc. that mentioned the protected area(s). We compiled gray literature and advocacy documents from all NGOs active in the area around the protected area(s), relying on the NGOs' online presence and publications. Gray literature also included reports written by government agencies and research institutions.

Within our four categories of documents, we further sub-divided the documents by the spatial scale of their focus: local, provincial, and national (Table S1).

Table S1. Documents assessed in the discourse analysis. Full citations for these documents are provided at the end of this appendix section.

Case study	Scale	Management	Policy	Gray literature	Advocacy
Jamanxim (n = 59)	Local (Jamanxim NF)	2	4	0	9
	State (Pará)	0	1	3	8
	National (Brazil)	3	7	17	5
Tambopata-Bahuaja-Sonene	Local (Tambopata National Reserve,	4	1	7	8

(n = 50)	Bahuaja-Sonene NP)				
	State (Madre de Dios, Puno)	0	0	10	6
	National (Peru)	0	4	5	5
Amboró-Carrasco (n = 42)	Local (Amboró NP, Carrasco NP, Amboró Integrated Management Natural Area)	2	4	9	5
	State (Santa Cruz, Cochabamba)	0	1	4	2
	National (Bolivia)	0	2	11	2

We established the initial themes for coding our discourse analysis through 1) a literature review of variables included in tropical deforestation models (see Appendix 1 for details and reference list) and 2) a word count of all document using NVivo 12 [2]. We included words or phrases that appeared across the majority of documents as initial themes (Table S1).

Table S2. Initial and emergent themes for the discourse analysis, as well as potential spatial and quantitative proxies.

Type of theme	Theme	Potential proxy variable(s)
Initial themes		
Drivers	Physical and economic accessibility	- Distance to roads - Elevation, slope, aspect - Distance to navigable rivers - Distance to cities (markets) - Distance to previously deforested land
	Population pressure and expansion	- Population density - Population change - Presence of settlements
	Suitability for agriculture	- Elevation, slope, aspect

		- Precipitation - Soil moisture
	Economic activity and poverty	- GDP - Poverty rate
	Demand for land	- Head of cattle per municipality
Mediators	Urbanization	- Urbanization rate
	Governance	- Zoning
Emergent themes		
Drivers	Ranching	- Head of cattle per km^2
	Population pressure	- Population growth - Migration - Expanded settlements
	Mechanized agriculture	- Farm equipment - Mean farm size
	Resource extraction	- Logging - Unauthorized logging - Mining - Unauthorized mining
	Land tenure; settlements; land grabbing	- Agrobusiness expropriation - Indigenous land titling - Land titling - Land grabbing - Pre-existing land claims in the protected area - Smallholder occupation
	Forest degradation and fires	- Distance to fire perimeters - Fire density
	Infrastructure development	- Distance to proposed dams - Distance to proposed railroads - Distance to transmission lines
	Globalization	- Lack of commodity traceability

	Protected area downgrading, downsizing, and degazettement	- Proposed PADDD events - Implemented PADDD events
Mediators	Sustainable development	- Presence of agroforestry initiatives - Presence of non-timber forest product concessions - Presence of ecotourism
	Land tenure	- Presence of Indigenous Territories - Land titling
	Education	- Rate of high school completion
	Increase area under protection	- Proposals for new or expanded protected areas - Establishment of new or expanded protected areas - Creation of communal land reserves - Creation of private conservation reserves
	Economic incentives for forest conservation	- Boycotts - Carbon markets - Payments for ecosystem services - REDD+
	State governance	- Enforcement - Monitoring - State capacity - Regulatory jurisdiction - Territorial planning - Governance quality
	Non-state governance	- Level of local participation - NGO projects - Environmental education and public outreach
	Government policies	- Agricultural policies - Climate change policy - Forestry policies - Land use policies - Mining concessions

Two co-authors (MMN and ES) then coded a subsample of documents (n = 30), including at least one document from each category of document and spatial scale, using NVivo. For this initial coding exercise, we used the initial set of themes and two umbrella themes, "drivers" (factors associated with forest conversion to agriculture) and "mediators" (factors discussed as potential solutions to deforestation). Throughout this coding process, when documents discussed factors related to increasing or decreasing deforestation that were not found in our list of initial themes, we coded the relevant text using the new umbrella themes of "drivers" and "mediators." If a specific driver or mitigating factor occurred in more than three documents, we categorized it as an emergent theme (Table S2). We then coded all 151 documents, using the full list of initial and emergent themes.

We next identified potential spatial and quantitative (or categorical) proxies for the initial and emergent themes through literature review and the best available data [3,4], to enable integration of the discourse analysis results into our land use change models (Table S2). For example, the emergent theme of "infrastructure development" had several potential proxies: distance to proposed dams, distance to proposed railroads, and distance to proposed transmission lines. However, data availability limited our ability to operationalize these proxy variables. As a result, we were unable to include some emergent themes (e.g., "globalization" and "non-state governance") in our land use change models.

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Here, we provide complete citations for all documents included in the discourse analysis for the three case study sites.

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Appendix S3: Models of land use change in the three case study sites

Table S3. Variables included in each model/site. x = included, o = included but dropped due to collinearity

Variable	Jamanxim				Amboró-Carrasco				Tambopata-Bahuaja-Sonene			
	LUC	DA	LUC & DA	Refined LUC & DA	LUC	DA	LUC & DA	Refined LUC & DA	LUC	DA	LUC & DA	Refined LUC & DA
Aspect	x		x		x		x	x	x		x	
Slope	x		x	x	x		x	x	x		x	
Elevation	x		x	x	x		o	x	x		x	x
Distance to roads	x		x	x	x		x	x	x		o	
Distance to rivers	x		x		x		x		x		x	
Distance to mines	x		x	x	x		x	x	o		o	
Distance to cities	x		o		x		x	x	x		o	
Crop suitability	x		x	x	x		x	x	x		x	x
Precipitation	x		x	x	x		o		x		x	x
Soil moisture	x		x	x	o		o		o		o	
Population density	x		x	o	x		x		x		x	
Poverty rate	x		o		x		x		o		o	
Neighborhood effect	x		x	x	x		x	x	x		x	x
Management status	x		x	x	x		x	x	x		x	x
Distance to agriculture		x	x	x		x	x	x		x	x	x
Distance to fires		x	x	x		x	x	x		x	x	x

Fire density		x	x	x		x	x	x		x	x	x
Distance to unauthorized mines		x				x	x	x		x	o	o
PADDD		x		x						x	o	x
Unallocated public land		x	o	o								
Cattle		x	o	x		x	x	x				
Distance to proposed railroads		x		x								
Distance to proposed dams		o	o	o								
Agricultural reform settlements		x		x								
Distance to tourism						x	x	x		x	x	x
Payments for ecosystem services						x	x	x				
North/south						x	x	x				
Land tenure						x	x	x				
Distance to control posts										x	x	x
Distance to Indigenous community concessions										o	o	o
REDD+ concessions										x	x	x

Table S4. Results of the modified version of the refined LUC & DA model for Tambopata-Bahuaja-Sonene. All variables are scaled. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Variable	Estimate (standard error)
Intercept	-82.5960*** (7.4388)
Elevation	-4.5643 (2.5895)
Distance to rivers	0.0615 (0.0724)
Crop suitability	0.1874* (0.0918)
Precipitation	0.3027 (0.2485)
Neighborhood difference	0.2103*** (0.0145)
Location in Bahuaja-Sonene National Park	-0.0663 (0.4172)
Locations within 10km buffer	-0.4051 (0.2868)
Location within 20km buffer	-0.4698 (0.3137)
Distance to agriculture	-79.4467*** (7.8268)
Distance to fires	-0.3215* (0.1489)
Fire density	0.1025** (0.0332)
Distance to unauthorized mines	-0.3922 (0.2057)
PADDD proposals	1.3232*** (0.3676)
Distance to tourism	0.3840* (0.1591)
Distance to control posts	0.5952** (0.2156)
REDD+ concessions	-1.0696 (1.0410)

Table S5. LUC model results for the three case study sites. All variables are scaled. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Standardized variables	Estimate (Standard error)		
	Jamanxim	Amboró-Carrasco	Tambopata-Bahuaja-Sonene
Intercept	-4.3320*** (0.0237)	-5.7236*** (0.0885)	-16.7404*** (1.3972)
Aspect	0.0023 (0.0098)	-0.0662*** (0.0107)	0.0898 (0.0658)
Slope	-0.2239*** (0.0128)	-0.9960*** (0.0240)	0.0377 (0.2490)
Elevation	-0.2187*** (0.0223)	-0.4686*** (0.0267)	-12.8046*** (2.0841)
Distance to roads	-1.3806*** (0.0245)	-0.0607** (0.0229)	-0.1944 (0.1678)
Distance to rivers	0.0050 (0.0116)	-0.0118 (0.0093)	0.3516*** (0.0581)
Distance to mines	-0.4203*** (0.0267)	-0.1718*** (0.0206)	
Distance to cities	-0.0240 (0.0178)	-0.2034*** (0.0200)	-0.2502 (0.1349)
Crop suitability	0.0618*** (0.0157)	0.0439*** (0.0129)	0.3291*** (0.0884)
Precipitation	-0.1308*** (0.0116)	-0.0370 (0.0201)	0.6690*** (0.1796)
Soil moisture	-0.4274*** (0.0150)		
Population density	-0.3453*** (0.0228)	0.0104 (0.0101)	-0.1939 (0.2299)
Poverty rate	0.0228 (0.0186)	-0.0191 (0.0231)	
Neighborhood difference	0.4607*** (0.0055)	0.4306*** (0.0068)	0.4202*** (0.0125)
Locations within 10km buffer	0.6998*** (0.0258)	2.1212*** (0.0945)	0.5744* (0.2816)
Location within 20km buffer	0.6379*** (0.0300)	2.1819*** (0.0945)	0.6880* (0.3090)

Location in Amboró Natural Integrated Management Area		1.7809*** (0.0983)	
Location in Carrasco National Park		0.9813*** (0.0992)	
Location in Bahuaja-Sonene National Park			1.2923*** (0.2829)

Table S6. DA model results for the three case study sites. All variables are scaled. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Standardized variables	Estimate (Standard error)		
	Jamanxim	Amboró-Carrasco	Tambopata-Bahuaja-Sonene
Intercept	-8.5166*** (0.0970)	-9.1621*** (0.0998)	-149.5658*** (8.7890)
Distance to agriculture	-3.1460*** (0.0468)	-7.0982*** (0.1117)	-153.9634*** (9.2666)
Distance to fires	-4.6699*** (0.1384)	-1.1629*** (0.0638)	-0.2756* (0.1295)
Fire density	0.4830*** (0.0079)	0.2725*** (0.0094)	0.0944*** (0.0268)
Distance to unauthorized mines	-0.0702*** (0.0150)	-0.1582*** (0.0137)	-0.1934 (0.1305)
PADDD proposals	-0.0619* (0.0262)		1.5873*** (0.2142)
Unallocated public land	0.0800** (0.0272)		
Cattle density	0.0899*** (0.0235)	0.0216* (0.0101)	
Distance to proposed railroads	-0.3927*** (0.0173)		
Agricultural reform settlements	-0.2750*** (0.0408)		
Distance to tourism		0.0110 (0.0142)	0.3272** (0.1060)

Presence of PES		-1.0734*** (0.0961)	
North/south location		0.2922*** (0.0308)	
Land tenure		0.2560*** (0.0323)	
Distance to control posts			0.2913 (0.1539)
REDD+ concessions			-0.9238 (1.0223)

Table S7. LUC & DA model results for the three case study sites. All variables are scaled. * p < 0.05, ** p < 0.01, *** p < 0.001

Standardized variables	Estimate (Standard error)		
	Jamanxim	Amboró-Carrasco	Tambopata-Bahuaja-Sonene
Intercept	-8.2192*** (0.1018)	-7.4524*** (0.1215)	-85.4631*** (7.4955)
Aspect	0.0112 (0.0107)	-0.0515*** (0.0109)	0.0934 (0.0648)
Slope	-0.2654*** (0.0138)	-0.6247*** (0.0243)	-0.7018* (0.2730)
Elevation	-0.1724*** (0.0249)		-4.9134 (2.5628)
Distance to roads	-0.0890** (0.0278)	-0.1286*** (0.0240)	
Distance to rivers	0.0426** (0.0134)	-0.0029 (0.0093)	0.0994 (0.0692)
Distance to mines	0.0736* (0.0314)	-0.1534*** (0.0219)	
Distance to cities		-0.1115*** (0.0214)	
Crop suitability	-0.0435** (0.0165)	0.0460*** (0.0136)	0.1779* (0.0901)
Precipitation	-0.0096 (0.0160)		0.0744 (0.2172)

Soil moisture	-0.1452*** (0.0223)		
Population density	-0.0816*** (0.0203)	-0.0383*** (0.0114)	-0.8240*** (0.2483)
Poverty rate		-0.1679*** (0.0313)	
Neighborhood difference	0.3235*** (0.0056)	0.2462*** (0.0073)	0.2108*** (0.0145)
Locations within 10km buffer	0.3401*** (0.0495)	0.2313* (0.0976)	-0.4674 (0.2868)
Location within 20km buffer	0.1602** (0.0547)	0.3593*** (0.0983)	-0.5973 (0.3075)
Location in Amboró Natural Integrated Management Area		0.1246 (0.1031)	
Location in Carrasco National Park		-0.1954 (0.1056)	
Location in Bahuaja-Sonene National Park			0.2571 (0.2949)
Distance to agriculture	-2.2181*** (0.0451)	-4.5197*** (0.1089)	-81.3137*** (7.9017)
Distance to fires	-4.6364*** (0.1433)	-0.6521*** (0.0701)	-0.3651* (0.1511)
Fire density	0.4990*** (0.0081)	0.3083*** (0.0103)	0.0895** (0.0329)
Distance to unauthorized mines	-0.1390*** (0.0209)	-0.2182*** (0.0211)	
PADDD proposals	0.2238*** (0.0455)		
Unallocated public land			
Cattle density		0.0018 (0.0127)	
Distance to proposed railroads	-0.2753*** (0.0263)		
Agricultural reform settlements	-0.0608 (0.0432)		
Distance to tourism		0.0297 (0.0170)	0.5089*** (0.1441)

Presence of PES		-0.8536*** (0.0973)	
North/south location		-0.1791*** (0.0411)	
Land tenure		0.1965*** (0.0339)	
Distance to control posts			0.5055** (0.1831)
REDD+ concessions			-1.0936 (1.0422)

Table S8. Refined LUC & DA model results for the three case study sites. All variables are scaled. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Standardized variables	Estimate (Standard error)		
	Jamanxim	Amboró-Carrasco	Tambopata-Bahuaja-Sonene
Intercept	-8.1877*** (0.1017)	-7.2218*** (0.1238)	-82.9794*** (7.4752)
Aspect		-0.0520*** (0.0109)	
Slope	-0.2571*** (0.0137)	-0.5802*** (0.0248)	
Elevation	-0.1763*** (0.0242)	-0.2087*** (0.0302)	-5.1442* (2.6171)
Distance to roads	-0.1131*** (0.0276)	-0.1627*** (0.0235)	
Distance to rivers			0.0971 (0.0704)
Distance to mines	0.0708* (0.0313)	-0.1107*** (0.0213)	
Distance to cities		-0.0984*** (0.0212)	
Crop suitability	-0.0424* (0.0166)	0.0571*** (0.0134)	0.2140* (0.0914)
Precipitation	0.0520*** (0.0137)		0.5831** (0.2060)

Soil moisture	-0.1429*** (0.0218)		
Population density			
Poverty rate			
Neighborhood difference	0.3223*** (0.0056)	0.2474*** (0.0073)	0.2081*** (0.0144)
Locations within 10km buffer	0.2503*** (0.0464)	0.2447* (0.0975)	-0.4005 (0.2863)
Location within 20km buffer	0.0974 (0.0532)	0.3644*** (0.0981)	-0.4750 (0.3143)
Location in Amboró Natural Integrated Management Area		0.1690 (0.1025)	
Location in Carrasco National Park		-0.2407* (0.1048)	
Location in Bahuaja-Sonene National Park			-0.4593 (0.3577)
Distance to agriculture	-2.2141*** (0.0450)	-4.4802*** (0.1086)	-79.4273*** (7.8691)
Distance to fires	-4.6602*** (0.1434)	-0.5445*** (0.0696)	-0.3633* (0.1467)
Fire density	0.4892*** (0.0080)	0.2894*** (0.0101)	0.0985** (0.0332)
Distance to unauthorized mines		-0.1492*** (0.0154)	
PADDD proposals	0.1445*** (0.0436)		1.4351*** (0.3569)
Unallocated public land			
Cattle density	-0.0015 (0.0141)	0.0088 (0.0103)	
Distance to proposed railroads	-0.2542*** (0.0244)		
Agricultural reform settlements	-0.0922* (0.0432)		
Distance to tourism		-0.0013 (0.0171)	0.2320 (0.1389)
Presence of PES		-0.8467***	

		(0.0973)	
North/south location		-0.4360*** (0.0539)	
Land tenure		0.1955*** (0.0337)	
Distance to control posts			0.3472* (0.1768)
REDD+ concessions			-1.0189 (1.0383)