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Land conflicts from overlapping claims in Brazil's rural environmental registry

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Satellite-based land use monitoring and farm-level traceability offer opportunities for targeted zero-deforestation interventions on private lands. Brazil's Rural Environmental Registry (Cadastro Ambiental Rural, or "CAR"), a land cadaster based on self-declaration of property boundaries, was created to monitor compliance with national forest laws. It has become an important enabling measure for sustainable supply chain initiatives like the Amazon Soy Moratorium. However, CAR enrollment is increasingly used to bolster illegal land claims, putting it at the heart of land grabbing dynamics. Self-declaration of properties in the CAR offers a unique situation to study land conflicts and their impact on land use decisions on a large scale. We quantified competing land claims among 846,420 registrations in the Brazilian Legal Amazon and applied a series of generalized linear mixed-effects models. We determined that CAR overlaps are more prevalent on larger registrations, in more densely settled areas, and in areas with less secure land tenure. We tested how landholders respond to land conflicts, finding significantly more deforestation and declared legal forest reserve on lands with multiple claims. CAR overlap results in an overestimation of forest reserves by up to 9.7 million hectares when considering double-counted and deforested areas of reserves, highlighting an overlooked form of Forest Code noncompliance. While the CAR continues to be used as evidence of land tenure, we conclude that the formalization of land claims through self-declarations is inadequate to decrease conflicts. CAR overlap information provides objective evidence of land conflict that authorities can leverage with field inspection to ensure peaceful occupation before issuing land titles.

zero-deforestation | sustainable supply chains | traceability | policy mix | enabling measures

Significance

Brazil is relying on a unique national land cadaster to balance a massive, export-oriented agricultural sector with conservation of the largest remaining forest reserve on the planet. This system relies on self-declaration of property boundaries, which provides transparency of illegal occupations and land conflicts, but also serves as a real, though illegitimate, basis for staking a land claim. This study suggests that self-declaration results in widespread conflicts among landholders in both competitive and speculative settings. We show that deforestation risk is elevated on contested lands, undermining environmental regularization. Authorities should leverage this overlap information to strengthen the land titling process, just as researchers should incorporate the effect of land conflicts into analyses and interpretations of policy effectiveness at the property level.

Environmental policies to promote sustainability can be based on strict command-and-control approaches or include mechanisms based on trust and self-declaration. The former involve higher enforcement costs and face political challenges. The latter benefit from greater social acceptance but may suffer from free-riding behaviors and conflicts. We use a unique land use policy implemented since 2012 to explore how more than 800,000 individual landholders across the Brazilian Amazon behaved when required to self-declare their property boundaries for monitoring compliance with forest laws. The evaluation of this policy provides insights into how private agents stake land claims and manage potential land use conflicts with their neighbors.

Tropical forests are at the forefront of global environmental crises around biodiversity loss, climate change, and indigenous rights. Numerous pledges have been made in recent years by governments, companies, and civil society groups to collectively end deforestation, resulting in a diverse landscape of—largely voluntary—public and private initiatives to better govern forest resources. Because agriculture for beef, soy, palm oil, and other nonstaple crops is the main driver of forest loss (1, 2), great expectations have been put into sustainable supply chain approaches for zero-deforestation commodities (3). Despite these commitments, high rates of deforestation persist due to implementation challenges, leakage, and incomplete market coverage—including increased consumption of commodities in producer countries where sustainability demand is weak (4). Furthermore, local drivers of deforestation like land speculation and land grabbing are beyond the reach of supply chain initiatives, illustrating that sustainable supply chains are just one component of broader policy mixes needed to solve deforestation at scale (5–7).

The most successful attempts to control deforestation have been polycentric approaches involving multiple, complementary interventions by networks of state and nonstate actors at different scales (8, 9). These policy mixes combine command-and-control measures like protected areas on forest frontiers with market-based incentives to protect forests that remain on private lands (10). Enabling measures are a critical but overlooked feature of these policy mixes. They provide institutional or technological support to regulatory and

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supply chain interventions, such as farmer technical assistance, secure land tenure, and satellite-based forest monitoring systems to track performance (6). Importantly, enabling measures can provide property-level traceability that facilitates more targeted policy options on private lands outside of protected areas, which are key to conservation and climate efforts (11–14). Current demand-side approaches depend on farm-level monitoring (15), such as the EU's due diligence regulation on imported deforestation (16), and corporate net-zero pledges addressing Scope 3 emissions across supply chains.

One of the few examples of a scaled-up land cadaster capable of providing this level of traceability is Brazil's Rural Environmental Registry (Cadastro Ambiental Rural, or "CAR"). The CAR was created to enforce Brazil's Forest Code, which requires as a general rule that at least 80% of landholdings in the Amazon biome be maintained under native vegetation as a forest reserve (*reserva legal*). Some exceptions apply to determine the obligation to restore illegal deforestation, depending on the size and location of the property (17). Landholders upload their self-declared property and forest reserve boundaries to the CAR, and the registration is linked to the individual's taxpayer identification number. Since 2012, a revision to the Forest Code requires all landholders in Brazil to enroll in the CAR (18), and the registry has become an important traceability tool for supply chain initiatives like the Amazon soy and cattle moratoria, which block the sale of commodities from deforested lands (19–23). The CAR provides a fundamental entry point into landholder behavior, voluntary and legal compliance, and polycentric governance approaches more broadly, but its role in conservation is still unclear.

The CAR was never intended to be used as a land title, but political changes pushed by the agribusiness lobby have enabled use of the CAR to illegally claim public lands, resulting in deforestation and rural land concentration (24–28). Fifty-six million hectares (Mha) of the Brazilian Amazon are undesignated public forests that do not belong to any tenure category specified by law (29, 30). A law (number 13 465) passed in July 2017 known as the "landgrabbers' law" ("lei da grilagem") granted amnesty to illegal occupants of public rural lands between 2005 and 2011. Subsequent actions temporarily extended amnesty to 2018 through an executive order that expired (MP 910). As of June 2024, proposed legislation in National Congress aims to increase the size of illegal occupations of public lands—up to 2,500 ha—that can receive a land title based on self-declaration with no on-site inspection (PL 2633/2020; PLS 510/2021). Meanwhile, the proportion of annual deforestation in the Brazilian Amazon occurring in undesignated public forests increased from 12% to 32% between 2016 and 2020 (31). Roughly a quarter of undesignated public forests have been illegally registered in the CAR as private landholdings, and most deforestation documented in undesignated forests has occurred in these registered areas (32). There is growing concern about the role of the CAR in facilitating land grabbing by serving as surrogate "proof" of land ownership, which is accompanied by land clearing to establish de facto possession (33, 34).

These policy developments demonstrate the importance of verifying the effectiveness of the CAR's self-declaration mechanism. In January 2023, the Lula administration renewed Brazil's commitment to combat deforestation with the launch of the 5th phase of the Action Plan to Prevent and Control Deforestation in the Legal Amazon (PPCDAM), including a target to end deforestation by 2030 (35). One of the proposed actions was to improve the CAR by canceling existing and blocking new registrations that overlap indigenous lands, protected areas, and federal lands without proof of land tenure. A federal decree issued in September 2023 also stated explicitly that the federal government cannot issue land titles in public forests and required that CAR registrations be validated before issuing land titles (Federal Decree 11866/2023).

These proposals focus narrowly on land conflicts between public and private lands, but significant overlaps between self-declared properties within the CAR have also been documented (13, 34, 36, 37). The link between these intra-CAR conflicts and environmental regularization has not been explored. So far, researchers have side-stepped the issue by excluding CAR registrations with significant overlap or by applying hierarchical rules to rectify overlaps (*SI Appendix*). Collective action theory suggests that when faced with resource commons dilemmas, some land managers will grab resources in a free-riding or confrontational strategy, while others will exercise voluntary restraint, avoid conflict, and cooperate with other users (38). Here, we take advantage of the information contained in areas of overlap to investigate land use decisions and their implications for polycentric forest governance.

The objectives of this study are to understand *i*) the degree of private landholder conflicts within the CAR; *ii*) whether landholder conflicts are more pervasive in areas of less secure land tenure; and *iii*) how landholders respond to conflicts. We quantified overlapping land claims for 846,420 properties in the Legal Amazon enrolled in the CAR from 2014 to 2021, applying a methodology that minimizes incidental overlaps from duplicate entries, canceled registrations, and measurement errors (*SI Appendix*, *Methods*). We fit generalized linear mixed-effects models (GLMMs) to understand which administrative, socioeconomic, and environmental factors are associated with higher levels of overlap, examining how CAR overlap varies by property size. Additionally, we tested for statistical differences in aggregate landholder responses to competing CAR claims, quantifying patterns of deforestation and areas of legal reserve declared on contested lands. Our findings reveal that intra-CAR landholder conflicts pose a serious risk to forest conservation policies on private lands and that metrics of CAR overlap can help identify hotspots of land conflict for prioritizing land tenure formalization.

Results

Overlap Among Properties Registered in the CAR is Pervasive and Increasing Over Time. First, we examined the trend of overlapping CAR registrations across states and landholder size classes and used ANOVA to test for increases in CAR overlap over time. From the earliest phase of implementation (2014, 2015, 2016), notable overlap (~5%) was present within the registered CAR area in the Legal Amazon. The amount of overlap has increased significantly over time (see Methods Statistical Analysis; *SI Appendix*, Fig. S4), with 16% of the registered area, or 35.4 Mha, having more than one claim in the region by 2021 (Table 1). Half of registered properties had at least one competing land claim in 2021 (n = 423,395). At least 10% of registered lands were overlapped in each state, except for Tocantins with only 2% of CAR overlap. CAR overlap was most pervasive in Acre, which averaged nearly 40% overlap and a median area of 8.48 ha of overlap—5× larger than Pará, the state with the next largest median area of overlap (Table 1). The number of CAR overlaps increased significantly with property size, but the relative proportion of the property that was contested was similar across size classes (Table 1). Hotspots of CAR overlap in Fig. 1 arise from clusters of larger properties that share overlap with dozens of smaller properties, and coincide with regions of documented land conflict—e.g., the Transamazon Highway corridor in southern Amazonas (27) (Fig. 1).

Table 1. Descriptive statistics for overlaps from the 2021 CAR in the Brazilian Legal Amazon (n = 846,420) by state, property size class, and biome

State	Num. CAR21 records	Gross CAR21 area (ha)	Net CAR21 area (ha)	CAR21 area overlapped	Mean num. overlaps (sd)	Median area overlap (IQR) (ha)	Mean % property overlap
Acre (AC)	39,205	5,915,212	4,944,484	16%	1.86 (3.20)	8.48 (36.03)	39%
Amazonas (AM)	57,558	33,239,926	23,881,880	28%	1.08 (3.80)	0.58 (13.66)	25%
Amapá (AP)	7,574	2,766,447	2,307,748	17%	1.13 (10.31)	0.99 (43.43)	33%
Maranhão (MA)	143,747	19,955,269	15,657,270	22%	1.58 (10.38)	1.45 (13.30)	30%
Mato Grosso (MT)	148,197	74,433,311	63,083,099	15%	0.86 (1.91)	0.87 (14.06)	21%
Pará (PA)	234,376	51,012,299	44,743,028	12%	1.08 (5.89)	1.68 (19.41)	25%
Rondônia (RO)	132,819	12,900,405	11,631,930	10%	0.85 (1.65)	1.44 (8.08)	22%
Roraima (RR)	13,962	5,645,101	4,636,530	18%	1.12 (2.17)	1.30 (39.31)	23%
Tocantins (TO)	68,982	19,231,813	18,773,024	2%	0.34 (0.85)	0.16 (1.15)	5%
Property size							
Small (<4 mf)	745,448	47,396,992	n/a	n/a	0.84 (1.76)	0.97 (9.62)	24%
Medium (4 -15 mf)	68,903	42,396,585	n/a	n/a	1.61 (2.53)	5.24 (123.43)	22%
Large (>15 mf)	32,069	135,306,206	n/a	n/a	5.15 (27.02)	22.87 (1022.81)	25%
Biome							
Amazon	641,576	161,533,219	133,219,033	18%	1.15 (6.29)	1.51 (15.77)	26%
Cerrado	201,262	58,343,541	52,115,982	11%	0.79 (2.60)	0.60 (5.67)	18%
Pantanal	3,582	5,223,023	4,323,978	17%	1.07 (1.73)	1.70 (23.60)	22%

Gross area represents the total area registered in the CAR and includes overlaps, while net area represents the dissolved footprint of the registered land area. Area overlapped represents the percent of the gross area that has more than one claim. While gross and net areas are aggregated, median area and mean % property overlap are based on property level statistics. IQR = Interquartile Range and sd = standard deviation.

CAR Overlaps are More Prevalent on Larger Registrations, in More Densely Settled Areas, and in Areas with Less Secure Land Tenure. Next, we investigated which factors are associated with property overlaps in the CAR, using Poisson GLMMs for the number of property overlaps. We selected fixed predictor variables related to land tenure and accessibility (*SI Methods* and *SI Appendix*, Table S3 on variable selection). We controlled for variation among states and municipalities by including them as separate random intercept terms.

Regional model. Our results across the Legal Amazon (846,420 registrations) indicated that property size was the single largest factor associated with CAR overlap—larger registrations had greater numbers of overlaps ($P < 0.001$) (Fig. 2 and *SI Appendix*, Table S4). As a measure of property density, a greater proportion of a municipality under private land claims (i.e., footprint of CAR registrations and titled properties) was the next most influential predictor of CAR overlap ($P < 0.001$). Land tenure factors had notable associations with CAR overlap. Registrations that coincided with titled lands averaged 10 to 15% fewer overlaps than untitled registrations ($P < 0.001$), whereas CAR registrations on undesignated federal and state lands averaged about 5% more overlaps ($P < 0.001$). This trend was accentuated in Rondônia, Roraima, and Acre, where CAR overlaps were 6 to 8% higher on undesignated lands. Settlements—public lands that have been transferred to landless families through colonization programs in the Amazon region—had a smaller, but still significant, association with fewer CAR overlaps ($P < 0.01$). The exception was Pará, with significantly higher overlap in settlements ($P < 0.001$). Public lands under strict use protections like national parks and indigenous territories did not have a meaningful effect on the number of CAR overlaps ($P = 0.250$). Relatively few properties were registered on these lands, so our model tested for the effect of proximity to these protected areas on the number of overlaps at the municipality level.

The effects of land accessibility predictors on CAR overlap were more variable. Biophysical factors like slope and forest cover were not associated with number of property overlaps, but more CAR overlaps were found closer to roads ($P < 0.001$). Our model predicted that the number of property overlaps decreases by 1 every 200 m from the nearest road (*SI Appendix*, Fig. S5). More agricultural credit distributed at the municipality level was also associated with significantly fewer CAR overlaps ($P < 0.001$).

Variation in CAR overlap by landholder size. Models fitted by landholder size followed the trends of the regional model, with several notable differences for land tenure variables across size classes (*SI Appendix*, Tables S5-S7). Small registrations had significantly less overlap ($P = 0.002$) in municipalities with more protected lands. CAR overlap was significantly associated with undesignated public lands for small registrations only ($P < 0.001$), likely because they were situated in more densely populated areas closer to roads (see SI Results). On titled lands, we found significantly less overlap on medium ($P < 0.001$) and large ($P < 0.001$) properties, but more overlap on small properties ($P < 0.001$).

Landholders Use Clear Strategies to Respond to Land Conflicts that Vary by Region. Finally, we tested the hypothesis that landholders respond to conflicts in the CAR by either clearing contested areas (confrontational strategy) or by declaring them as legal reserves (conflict avoidance strategy). Using a 2019 version of the CAR to improve temporal alignment with deforestation data, we implemented Chi-square analyses at the subproperty level to test whether there is more deforestation or legal reserve declared in overlapped regions of properties.

Deforestation in overlaps. Landholders cleared relatively more forest in contested parts of their properties than in areas without overlapping CAR claims. Across the subset of six states included in the subproperty level analysis (see *Methods*), five had significantly more deforestation in overlapped versus nonoverlapped regions of properties (*SI Appendix*, Table S8). Contrary to the regional trend, in Amazonas only 27% of municipalities had significantly more deforestation in overlapped regions of properties. Overall,

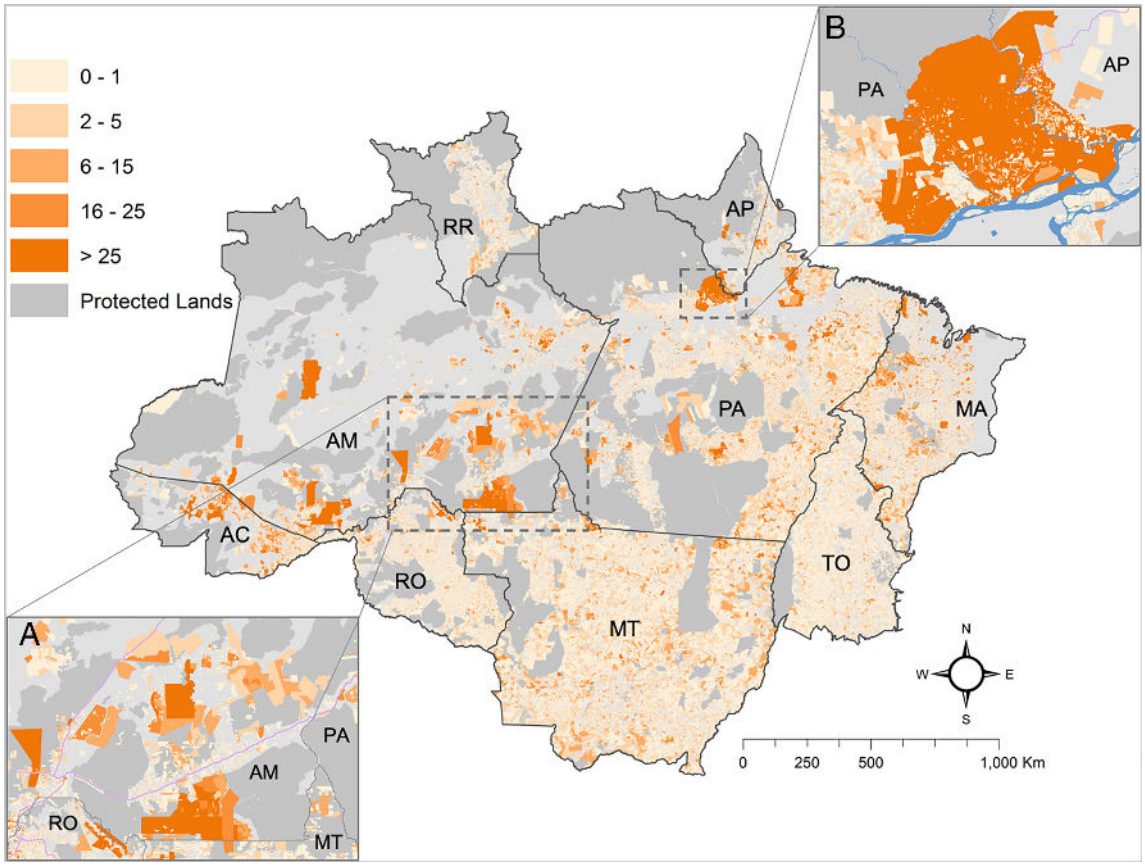

Fig. 1. The number of competing land claims on declared properties in the Brazilian Legal Amazon from the 2021 CAR (n = 846,420 registrations). Panels provide a closer look at two regions of interest with known land conflicts. (*A*) the Transamazon highway (BR-27) and BR-319 corridors in southern Amazonas (AM) and (*B*) conflicts between small farms and super properties in the municipality of Almeirim along the border between Pará (PA) and Amapá (AP). Purple lines indicate highways.

we observed 21% more deforestation in overlaps (660,842 ha) than expected by random chance alone (525,346 ha). This was particularly pronounced in Acre and Rondônia, with 41% and 46% more deforestation in overlaps, respectively.

Legal reserve declared in overlaps. At the regional scale, landholders also designated relatively more (27%) legal reserve in contested parts of their properties than in areas without overlapping CAR claims (*SI Appendix*, Table S9). This was the trend for 85% of municipalities in the study region (n = 373). In Pará, 39% more legal reserve was observed in overlaps than expected by random chance alone. Inside regions of CAR overlap across the study region, 48% of the area declared as legal reserve is overlapped, equating to 9,410,467 ha of legal reserve that is registered by more than one landholder in CAR, or an average of 21,534 ha per municipality.

Land conflict response hypothesis. Our Chi-square analysis indicates that more than half of the municipalities in the study region followed our hypothesis of either more deforestation (n = 17) or more legal reserve declared (n = 211) in contested parts of properties (Fig. 3). In remote regions of the Brazilian Amazon, landholders appear to respond to conflicts through an avoidance strategy by declaring legal reserve in contested areas. On more active frontiers, such as the Acre-Amazonas-Rondônia border region, deforestation is more prevalent in overlaps, suggesting landholders are more actively staking their claim (*SI Appendix*, Fig. S7). Both confrontational and conflict avoidance strategies were observed in 37% of municipalities (n = 162) where significantly more deforestation and legal reserve was observed in overlapped parts of properties. Across the study region, this equates to 292,108 ha of legal reserve declared within CAR overlaps that was deforested during the study period.

Discussion

The CAR has transformed strategies to control deforestation at the property level in Brazil, offering a potential model for other nations managing critical forest resources on large frontiers. As a public land cadaster with millions of subscribers, the CAR provides a level of traceability that has allowed policymakers and soy and cattle traders to better enforce their policies to reduce deforestation. However, there are tradeoffs between the volume and quality of data generated by the CAR that challenge its utility for land use governance. Our analysis reveals that land conflicts—competing claims represented by overlapping CAR registrations—are prevalent throughout the Brazilian Amazon. Our efforts to reduce "incidental" overlaps caused by measurement error, duplicate registrations, and settlement boundaries, indicate that the remaining high levels of overlap represent actual land conflicts on the ground. Landholders are responding to competing claims on their properties through both confrontational and conflict avoidance strategies, illustrating how conservation gains established by one landholder can be offset by a competing landholder. These findings highlight how intra-CAR conflicts among private landholders—not just CAR overlaps with public lands—challenge environmental regularization, land titling, and zero-deforestation commitments.

Land Speculation and Scarcity. We provide evidence that CAR overlap is associated with more deforestation in most states and that these land conflicts are exacerbated under more insecure land tenure. CAR registrations coinciding with titled lands and settlements—i.e., areas of land tenure regularization with strong legal protections—featured less overlap, whereas registrations on

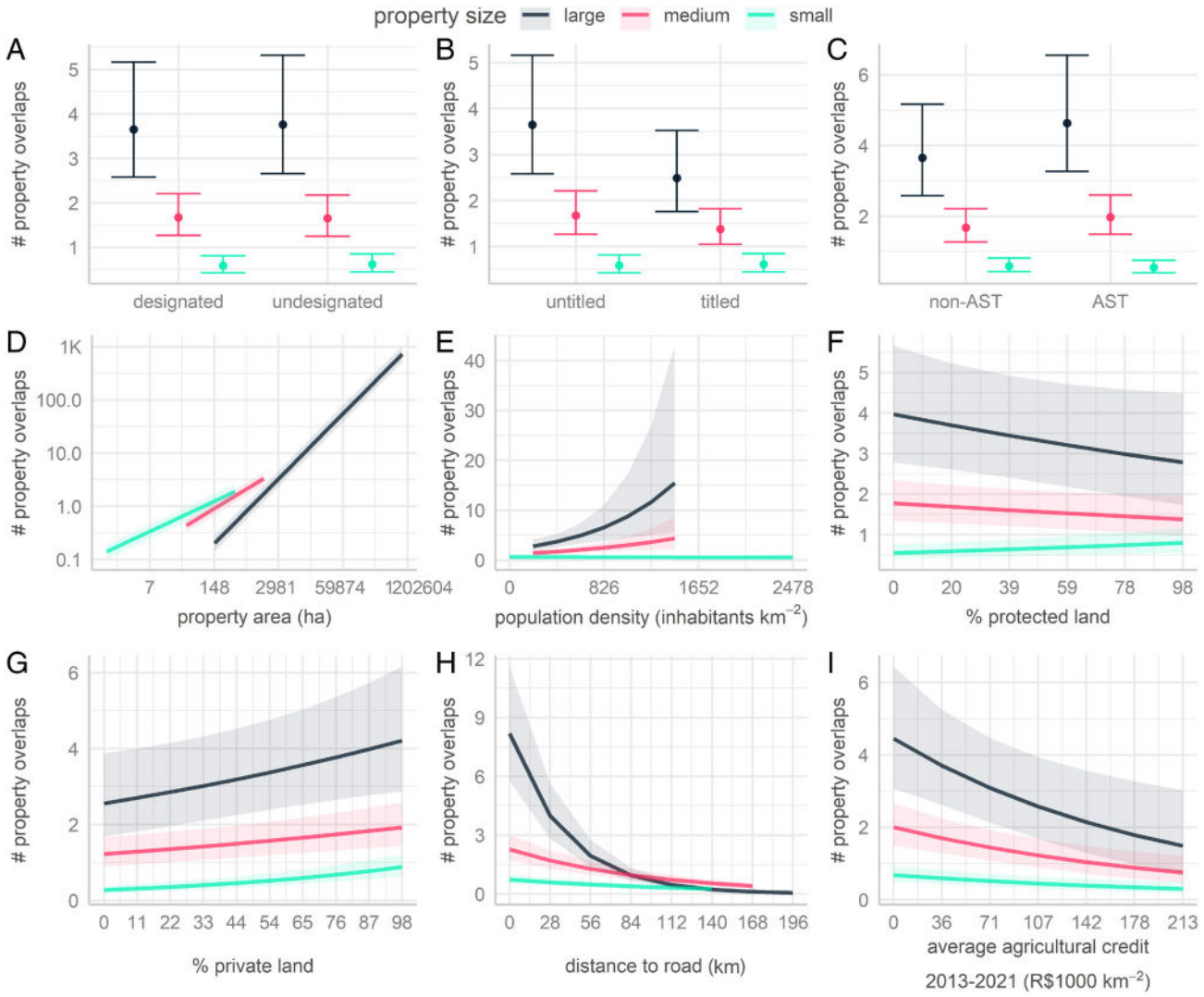

Fig. 2. Marginal effects plots for statistically significant fixed terms related to land tenure and accessibility in a Poisson generalized linear mixed-effects model of the number of property overlaps in the 2021 CAR. Effects are plotted by landholder size classes as defined by number of "fiscal modules" (mf): 1) small (< 4 mf), 2) medium (4 to 15 mf), and 3) large (>15 mf). In panels *A–C*, we plot the predicted number of property overlaps for discrete predictors, where points are means and bars are 95% CI. For continuous predictors in panels *D–I*, we plot the model predicted number of property overlaps as a function of continuous predictors, where lines are model-predicted marginal means and shaded regions are 95% CI. *SI Appendix*, Tables S4–S7 for model coefficients and *SI Appendix*, Fig. S6 for fixed and random effects plots.

undesignated public lands—i.e., federal and state lands without a legally specified designation—featured more overlap. The phenomenon of overlapping registrations is thus partially due to the speculative use of CAR to appropriate lands with weaker protections. Concurrent with recent land grabbing via CAR, we show that a "land rush" dynamic is also occurring, whereby claims have become increasingly overlapped since 2015 (*SI Appendix*, Fig. S4). Our finding of higher CAR overlap in areas where less agricultural credit was distributed lends evidence to the speculative use of CAR for claiming land. Land grabbers are unlikely to risk exposure by applying for credit, and they typically do not mount productive operations, opting instead to leave appropriated land under forest cover to avoid detection until it can be sold (27, 39). Incipient land markets and frontier remoteness may partially explain why Amazonas was the only state that did not have significantly more deforestation in overlaps. Competition among land speculators may not yet have reached a level where claimants begin to assert their claim through forest clearing.

We find that CAR overlap is not confined to regions of insecure land tenure on remote frontiers. Significant overlap occurs within the mesh of more developed landscapes that feature a high density of existing private lands and road accessibility. Overlap in this context is likely based more on land scarcity than speculation. We did not observe a strong spatial pattern of CAR overlap according to development frontiers (40, 41). Frontier-defining variables like population density, remaining forest cover, and proximity to protected areas had no association with CAR overlap in our regional model.

We calculated that forest reserves are overestimated by up to 9.7 Mha when accounting for overlapping and deforested areas of declared legal reserves. This is an overlooked form of noncompliance with the Forest Code stemming directly from CAR overlap. In their analysis of Forest Code compliance in the Amazon and Cerrado biomes, Rajão et al. estimated 2.3 to 2.5 Mha of illegal deforestation (21). We estimate that nearly 0.3 Mha of this occurred in areas with multiple claims. Our finding that over 9.4 Mha of legal reserve are claimed by more than one landholder suggests that the risk of illegal deforestation is high, and attributing liability to specific landholders presents a challenge for law enforcement.

CAR Overlap in Soy Regions. The soy sector has the most advanced zero-deforestation policies in the Brazilian Amazon but was excluded from our models since soy is not produced widely across

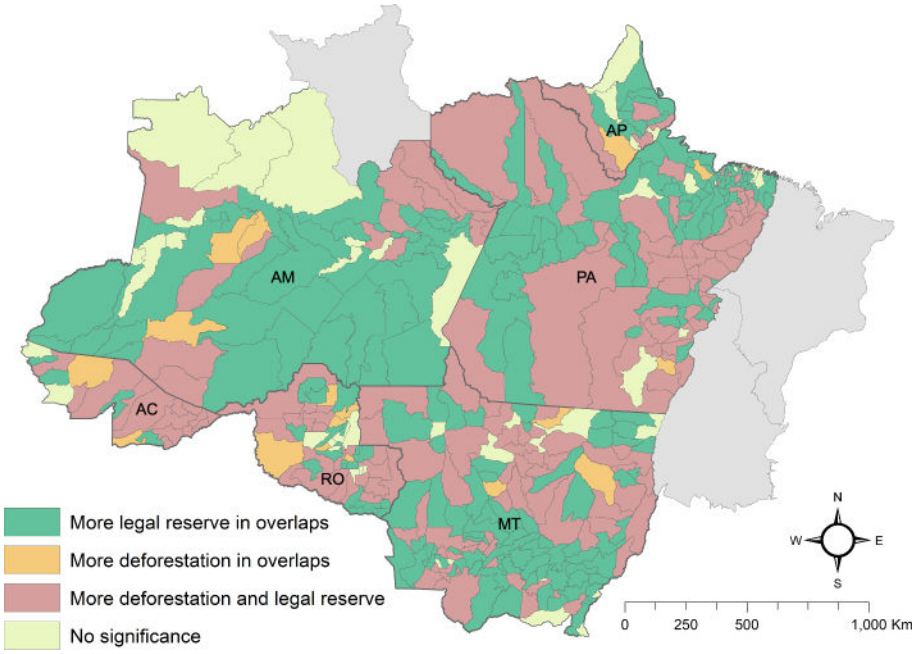

Fig. 3. The outcome of landholder response hypothesis testing from Chi-square analysis at the municipality level (n = 437). Municipalities with more legal reserve declared in overlaps (green) indicate that landholders are avoiding land conflicts, whereas municipalities with more deforestation in overlaps (orange) indicate that landholders are clearing land in response to conflicts. In municipalities shaded red, both landholder response behaviors are prevalent in overlaps, putting environmental regularization at risk. Municipalities where Chi-square analyses were not significantly different from the null expectation are shown in light green.

all states in the study region. An assessment of CAR overlap in the top soy-producing municipalities in 2020 [n = 105; combined 95% of soy produced in the study region (42)] indicates that regions of high soy production have comparatively less CAR overlap. On average, properties in the top soy-producing municipalities had 19% fewer overlaps and 33% less area overlap compared to the statewide trends in Table 1. The only exception was Rondônia, which had 22% more overlaps and 28% greater overlap area in soy municipalities. CAR registrations in top soy-producing municipalities are also, on average, 32% larger than properties in other municipalities, which contrasts with the regional trend of more overlap on larger properties. This could be the result of synergistic policy interactions between the CAR and supply chain initiatives like the Amazon Soy Moratorium (ASM), under which 90% of the soy produced in the Amazon is traded. An evaluation of ASM effectiveness found the greatest declines in deforestation on lands that were both monitored by the moratorium and registered in the CAR (23). Large ASM producers are more visible in global supply chains and reduced CAR overlap from more formalized producers is a likely cobenefit of improved supply chain governance.

Policy Implications. Previous research found variable impacts of CAR enrollment on reducing deforestation (43–46). It also showed that environmental registration can be an important first step in implementing deforestation policies that target private landholders, even before robust monitoring systems are in place for Forest Code enforcement (47). By the 2020s, enrollment of land in the CAR far outpaces the ability of authorities to verify claims, resulting in an expansion of area with unresolved land conflicts and increased deforestation risk. This has implications for both environmental regularization (i.e., Forest Code compliance) and the tenure regularization process for land titling. Below, we discuss how authorities can leverage the volume of landholder information to identify and respond to areas of conflict.

Environmental regularization. The phenomenon of CAR overlap is significant across states and landholder sizes, but the degree of conflict—i.e., the number and area of competing claims—increases dramatically with property size. An important question for authorities is, how much CAR overlap should trigger investigation or outright cancellation of a registration? Our study suggests that a property size threshold exists around 3000 ha. For properties <3,000 ha, the predicted number of competing claims is <5, yet for properties >3,000 ha, the number of overlaps increases exponentially with property size (Fig. 2). Any degree of overlap represents a land conflict, but focusing on larger properties helps prioritize limited staff resources. The system already includes automatic filters that flag CAR overlaps with protected public lands, classifying these registrations as "pending" and requiring review by authorities before registration can be completed (37). Similar filters could be applied for intra-CAR overlaps to resolve conflicts among private landholders more quickly. A potential risk, however, is the strategic enrollment by landholders to stay below this threshold and avoid additional screening (45).

To deter competing claims, environmental authorities can use CAR records to assign shared liability for illegal deforestation. Federal prosecutors already bring lawsuits against illegal deforesters in areas of overlap by adding all alleged owners of the land as defendants (48). This enforcement strategy ensures landholders take on legal risk when publicly claiming land.

Tenure regularization. Regularization of land claims through a system of self-declaration, as proposed by bills in National Congress, is prone to result in land conflicts. A more formal—but also more costly—process involving verification and certification by authorities is needed on top of the self-declaratory CAR process to minimize competing claims. Current laws allow the issuance of land titles without previous field inspection for parcels up to 4 fiscal modules unless they fall into some specific situations, including the existence of land conflict. We suggest the government use CAR overlap information as objective evidence of land conflict to trigger field inspections, determine the legitimate claimant, and verify the requirement of peaceful occupation before issuing a land title. Since state and federal laws on regularizing occupations of public lands differ (33), more coordinated multilevel governance is needed to reduce risk of corruption around land regularization at the local

level (27). Harmonizing environmental and tenure regularization processes must also be accompanied by a thorough revision of laws to decouple land clearing and occupation from tenure. Finally, to improve reliability of the CAR, the issuance of a land title should be automatically updated in the CAR information system (SiCAR) to eliminate fraudulent overlaps. Any registrations overlapping titled records should be immediately canceled.

Conclusion

Global forest governance remains a largely fragmented regulatory landscape of disparate actors. Its central focus on commodity agriculture leaves illegal deforestation beyond the reach of supply chain initiatives unaddressed. To unlock more transformative polycentric governance, better coordination among actors is needed to create policy synergies for cost-effectiveness and scaled up impact (49). As an enabling measure for both public and private land use policies, the CAR has potential to deliver a traceability system for voluntary supply chain initiatives that simultaneously ensures compliance with national forest laws. The ability to link individual landholders with high-resolution monitoring enables spatially targeted interventions, reduced transaction costs, and lowered costs of compliance and verification.

Methods

We conducted an analysis of overlapping CAR registrations at two spatial scales. At the property level, we quantified CAR overlaps using a 2021 version of the dataset (nine states). At the overlap level, we measured deforestation and declared legal reserve (LR) within property overlaps to explore which land use strategies have been adopted by landholders in response to conflicts. We used a 2019 CAR version (six states) for the overlap-level analysis to align with the temporal availability of deforestation data.

Data and Preprocessing. Registrations in the CAR are self-declared property boundaries and vary widely in verification status. We applied a series of preprocessing steps (*SI Appendix* Methods and *SI Appendix*, Fig. S2) to eliminate canceled records and incidental CAR overlaps that were unlikely to represent true land conflicts, such as aggregate boundaries (e.g., settlements) that contain smaller, individual parcels. We attempted to eliminate records representing the same person or family unit, as well as spatially similar records that likely represented land ownership transfers. To do so, we developed a duplicate filter that used criteria based on landholder information (available only in the 2019 CAR dataset), property sizes, and property spatial footprints to remove suspected duplicates, retaining only the most recent record.

We used a land cover dataset (BDT-CAR) developed by researchers at the Federal University of Lavras (UFLA) in collaboration with the Brazilian Forest Service to assist state governments with analyzing Forest Code compliance (50). This dataset draws on multiple sensors to provide high-resolution deforestation data, which was critical to identifying land use change in small contested areas. Maranhão, Tocantins, and Roraima were excluded from the overlap-level analysis because deforestation data were only available between 2008 and 2011 (*SI Appendix*, Fig. S1). LR data for 2021 were acquired from the Brazilian Forest Service.

Quantifying CAR Overlaps. For each CAR record, we computed the area of overlap (the subset of the property falling within other properties) and the number of overlaps (the number of properties it intersects) (Table 1). When calculating the number of overlaps, we excluded pairwise overlaps that measured less than 1 ha in area, to avoid marginal overlaps that could be due to measurement errors. For the overlap-level analysis, we additionally computed the area of deforestation and LR within the property boundaries and the subset of those measurements that resided within areas of CAR overlap. For accounting purposes, we dissolved the LR area before calculating overlap statistics, measuring the presence or absence of an LR claim (net area), rather than the total LR area claimed (gross area).

Statistical Analysis.

Increasing overlap over time. We used repeated measures single-factor ANOVA to test for statistical differences in the CAR overlap area over time. Year was used as the single factor and aggregate area of overlap at the municipality level was used as the within-group repeated measure, as registrations are repeated over time in the registry.

Predicting CAR overlaps. We used GLMMs with Poisson error distribution and log link function to understand which socioeconomic and environmental factors were most associated with private land conflicts. We chose to model the number of overlaps, rather than the proportion of overlap, to capture the number of actors involved in land conflicts, and to avoid interpretability problems arising from smaller registrations being entirely overlapped by a single larger registration.

We considered different sets of variables for model selection related to land tenure, accessibility, development potential, and deforestation in the study region (*SI Appendix*, Table S3). Pairs of predictor variables were selected (SI Methods) and assessed for colinearity before model fitting. Backward model selection based on AIC was used to select the final models. Random intercept terms for municipality (n = 772) and state (n = 9) were included to remove random variation, improving overall model fit. Models were fit using the lme4 package (51, 52) in R (v.4.3.1), and residuals were checked, showing no biases or heteroscedasticity.

Landholder response hypothesis testing. We tested the hypothesis that when confronted with land conflicts, landholders will either stake a claim in the contested regions of their properties by clearing land (i.e., more deforestation in overlaps), or avoid conflicts in these contested areas by leaving them as natural vegetation (i.e., more legal reserve declared in overlaps).

We developed upscaling formulas (*SI Appendix*, Tables S1, S2) to conduct a full spatial accounting of total overlap area, non-overlap area, deforestation area, non-deforestation area, LR area, and non-LR area for each municipality and state. We created a contingency table for each municipality/state with two categorical variables: 1) area CAR overlap (versus area non-overlap) and 2) area deforestation/LR (versus area non-deforestation/non-LR). Using the overlap-deforestation and overlap-LR contingency tables, we performed Chi-square tests for association at level $\alpha = 0.05$ and applied a Bonferroni correction for both the municipality-level tests (n = 427) and state-level tests (n = 6) (*SI Appendix*, Tables S8 and S9).

Data, Materials, and Software Availability. Data from Brazil's Rural Environmental Registry (Cadastro Ambiental Rural, or "CAR") and information on environmental regularization are available at https://www.car.gov.br/#/ (53). Code and analyses, including our dataset of the processed CAR with property overlap data and environmental and socioeconomic predictors, are available on GitHub: https://github.com/hoganhaben/CAR21_AmazonPropertyOverlap (54).

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