# Land-use and land-cover change shape the sustainability and impacts of protected areas

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**Protected areas (PAs) remain the dominant policy to protect biodiversity and ecosystem services but have been shown to have limited impact when development interests force them to locations with lower deforestation pressure. Far less known is that such interests also cause widespread tempering, reduction, or removal of protection [i.e., PA downgrading, downsizing, and degazettement (PADDD)]. We inform responses to PADDD by proposing and testing a bargaining explanation for PADDD risks and deforestation impacts. We examine recent degazettements for hydropower development and rural settlements in the state of Rondônia in the Brazilian Amazon. Results support two hypotheses: (*i*) ineffective PAs (i.e., those where internal deforestation was similar to nearby rates) were more likely to be degazetted and (*ii*) degazettement of ineffective PAs caused limited, if any, additional deforestation. We also report on cases in which ineffective portions were upgraded. Overall our results suggest that enhancing PAs' ecological impacts enhances their legal durability.**

protected area | hydropower | impact evaluation | land-use change | land-cover change

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Land-use and land-cover change (LULCC) reflect and shape the global interplay between economic development and biodiversity conservation. In the second half of the 20th century pursuit of economic development resulted in conversion of ∼24% of the earth's surface into cropland and loss of ∼35% of mangroves and ∼20% of coral reefs (1). Over the same period, global gross domestic product increased sixfold (an average 3.9% annual growth rate) (2), yet the global "aggregate capital stock" may have fallen because the economic proceeds from the depletion of natural capital are often consumed rather than invested in alternative forms of capital (3).

Given multiple objectives, many policies aim to shape LULCC to foster synergies or minimize tradeoffs between economic development and biodiversity conservation. Tradeoffs have been a central issue for protected areas (PAs) (4), which are the cornerstone of local, national, and international conservation policies. Over 200,000 PAs cover ∼19.8 million $km^2$ globally, equivalent to ∼14.7% of all terrestrial and inland water areas (5). PAs feature varied governance, from strict bans on anthropogenic activity to limited development rights in varied "extractive reserves" (6), yet most PAs aim to shape (including reverse) LULCC trajectories.

Participatory decision processes (7) and sophisticated software applications (8) inform PA siting and governance choices by facilitating complex calculations of conservation gains and economic opportunity costs influenced by biogeography, development patterns, and myriad other factors (4). As a result, PAs are often established on lands with low opportunity costs (9) and low levels of deforestation pressure, limiting the potential for PAs to have substantive conservation impacts. In the Brazilian Amazon in the state of Acre, for example, multiple-use PAs in areas of high deforestation pressure reduced deforestation more than other, more restrictive PAs (10). However, contexts and political regimes matter as this result did not hold in other Amazonian states (6).

We examine the interplay between LULCC and a widespread yet underappreciated phenomenon of removing PA legal protection: PA downgrading, downsizing, and degazettement (PADDD). "Downgrading" refers to a decrease in legal restrictions on the number, magnitude, or extent of human activities within a PA (i.e., legal authorization for additional human activities); "downsizing" is a decrease in size of a PA as a result of excision of land or sea area through a legal boundary change; and "degazettement" is the loss of legal protection for an entire PA (11). Since the turn of the 20th century over 2,349 (2,264 enacted and 85 proposed) PADDD events have been documented in 70 countries, affecting 1.7 million $km^2$, including areas of global biodiversity importance (12). The proximate causes of PADDD are related to industrial-scale resource extraction and development, local land-use pressures and land-tenure claims, and—to a lesser extent—conservation planning processes (13). Little is known about the risk factors for PADDD, although an initial analysis suggested that larger PAs nearer to population centers were more likely to experience PADDD (14). Initial studies suggest that the ecological impacts of PADDD are heterogeneous in tropical forests: PADDD accelerated deforestation and carbon emissions in Peninsular Malaysia and Peru (15) yet had no significant short-term impacts on deforestation in the Brazilian Amazon (16).

## Significance

Emerging evidence shows that the boundaries of protected areas (PAs) and their level of protection regularly change, yet little is known regarding the underlying causes of these legal changes and their impacts on ecosystems. For PA degazettements (i.e., protection removals) in the state of Rondônia in the Brazilian Amazon we show that the PAs less effective in stemming deforestation are more likely to be degazetted. For those already deforested PAs degazettement had limited, if any, additional impact on deforestation. Consistent with the scientific literature recognizing that governance shapes conservation outcomes, governance that improves PA outcomes also improves their legal durability. Our evidence on such relationships suggests directions for research and the need for policymakers to reexamine conventional wisdom regarding PAs.

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To advance the nascent understanding of relationships between PADDD and LULCC we propose and test a conceptual framework for characterizing the risks and impacts of PADDD. First, we suggest that the observed variation in both the risks and impacts of PADDD can be understood using a single conceptual framework, one which focuses on the processes that lead to PADDD events. Our framework is based on two simple ideas: (*i*) The conservation costs of PADDD (the biodiversity and ecosystem services forgone), as well as the development benefits of PADDD, vary across the landscape and (*ii*) bargaining between key actors in conservation and development would imply that PADDD is more likely to occur when conservation costs are low and when development benefits are high. Using the state of Rondônia in the Brazilian Amazon as a case study we empirically examine PADDD events associated with hydropower development and rural settlements. Rondônia was selected based on the availability of an adequate number of temporally opportune and spatially explicit PADDD events, all within a single governance unit. Drawing on our conceptual framework, we consider empirically the risk factors associated with these PADDD events, whether risks differ by proximate cause of PADDD, and the impact of these PADDD events on LULCC. We conclude with a discussion of the scientific and policy implications of our research, which provides a lens for examining the governance dynamics of PAs and other environmental interventions with implications for biodiversity conservation and other LULCC policies.

## Conceptual Framework: Bargaining

**PADDD Risk.** Government agencies with either conservation mandates (hereafter "conservation agencies") or economic development mandates ("development agencies") perceive variation in the net costs or the net benefits of potential PADDD events. Given the perceived variation in costs and benefits, we hypothesize that bargaining between agencies could determine which potential PADDD events occur. Given distinct interests among agencies, we expect that some PAs will remain protected while others may be downgraded, downsized, or degazetted. Even within a single PA each type of agency may value portions of the PA differently and negotiate the PA's legal future accordingly. Within-site-level heterogeneity and bargaining may explain PA downsizing events where only a portion of the PA loses protection.

Assuming equal bargaining power, four archetypal scenarios illustrate the governance implications of PA bargaining between conservation and development agencies (Fig. 1). A conservation agency may perceive high costs from a proposed PADDD event if, for example, the PA contains the habitat of charismatic species of high social value. If in that situation a development agency perceives relatively low benefits from PADDD, we would expect this potential PADDD event to be unlikely (Fig. 1, *Top Left*). However, where a potential PADDD event has lower conservation costs and higher development benefits, PADDD is expected to be more likely (Fig. 1, *Bottom Right*). For scenarios with high conservation costs paired with high development benefits, or low paired with low, bargaining outcomes are less clear (Fig. 1, *Bottom Left* and *Top Right*), although following Coase (17) the initial property regime may persist (i.e., PA remains protected).

In reality, the benefits of PADDD for economic development may vary widely. In Brazil and in other developing nations, for example, we expect high perceived development benefits when degazettement would facilitate construction of an electricity-generating dam (18). Because only some areas inside PAs have topographies suitable for dams, these PAs and specific sites within them may be particularly vulnerable to hydropower-related PADDD. For PADDD resulting from rural settlements, by contrast, we expect the perceived economic development benefits to

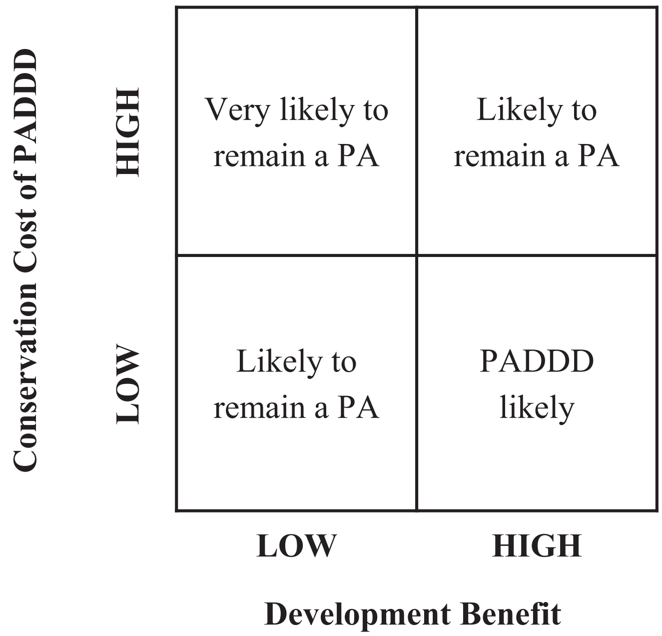


**Fig. 1.** Predicted outcomes of bargaining between conservation and development agencies under different scenarios of proposed PADDD. Here we consider four scenarios, presuming equal bargaining power among conservation and development agencies. The *y* axis considers the cost of PADDD to conservation and the *x* axis considers economic benefits from the development activities leading to PADDD. The four scenarios are (HIGH, LOW), (HIGH, HIGH), (LOW, LOW), and (LOW, HIGH). The text in each quadrant represents the potential outcome of the corresponding scenario. We acknowledge that this is an overly simplified model and, in reality, we anticipate bargaining power to differ across agencies and levels of government.

rise with the profitability of agricultural production that drives land clearing. Thus, PADDD associated with rural settlements is more likely among PAs with the potential for higher agricultural profits (e.g., nearer to roads), while other PAs might have limited economic potential and, therefore, development agencies may perceive low benefits of PADDD.

Similarly, the conservation costs of proposed PADDD events may vary considerably. Some PAs are inhabited by species or generate ecosystem services that conservation agencies perceive as highly valuable, implying high conservation costs of enacting PADDD. For PAs where such favored species reside, or key ecosystem services are generated, we expect strong resistance to PADDD by conservation agencies. Conversely, we expect conservation agencies to be more willing to bargain away PAs that feature already highly degraded habitats. Such lands may have limited conservation value and, thus, low conservation costs of PADDD.

Given the potential for conservation and development agencies to have differing perspectives on the net benefits from PADDD events, the agencies' relative bargaining power—which can vary widely over both governance settings and time periods, since regimes differ greatly—may influence the outcome of negotiations over PADDD. For instance, bargaining may occur between actors representing different levels of government (e.g., federal and state) and over the course of many years. In Rondônia, for example, formal degazettement of 10 protected areas occurred in 2010, when the state and federal governments negotiated for the Jirau dam construction (19, 20) (see *Materials and Methods*), yet the governance of these lands had been negotiated and renegotiated, codified and recodified, since at least 1990, when an initial land-use zoning plan was established.

Moreover, as outcomes of bargaining over PAs and previously enacted PADDD events emerge actors may update their beliefs about the relative strength of both conservation and development agencies. These outcomes and updated beliefs may affect actors' expectations about the future governance of other PAs (e.g., will other PAs continue to see their boundaries and regulations enforced or, alternatively, will they experience weakened enforcement and PADDD?). This may shape choices by both private- and public-sector actors.

Within a bargaining framework we might also expect various types of "trades" among actors. For instance, the creation of a new PA or the expansion of an existing PA may emerge as a form of "compensation" for a PADDD event (20, 21). Such spatial trading could even occur within the boundary of a single PA, where, for example, some land is suitable for hydropower and is already degraded while other lands within the same PA maintain intact forest cover and are home to favored species. In such a case, bargaining agencies might agree to downsize the PA for a dam while simultaneously upgrading the level of protection for the remainder of the same PA or adding other lands to the PA. In Amazon National Park (Pará, Brazil) a portion of the PA was downsized, while lands outside were added to the PA (23). Authors attribute this PADDD event to a complex interplay between development and conservation interests and existing policies, local land pressures, energy demands, and politics. Similarly, in Yosemite National Park within-PA compensation for PADDD occurred when lands suitable for resource extraction were removed from protection while other lands desirable for aesthetic value were simultaneously added (24).

As to what models we are arguing against when putting forth such implications of bargaining, we believe the natural leading alternatives involve just one interested party (e.g., either the conservation- or development-interested actor) dictating the outcome. In *SI Materials and Methods* we spell out such alternative predictions and why we reject them.

**PADDD Impact.** Our conceptual framework provides a lens for evaluating and interpreting the impacts of PADDD. Impacts are defined as the causal effects of an enacted PADDD event, relative to the counterfactual (i.e., what would have happened without PADDD). If PADDD occurs in a previously fully deforested PA, for instance, then such a PADDD event may not be able to have a substantive additional impact on forest cover or other ecological variables given the LULCC that preceded the PADDD event. Alternatively, if a PA has maintained the integrity of its forests then a PADDD event could have considerable impacts on forest integrity.

As anecdotal evidence from Brazil suggests (25), research examining the impacts of PADDD must recognize and account for the information that actors obtain from PADDD events that have occurred previously. Enacted PADDD events may be perceived as removing the commitment to protect that area, signaling a shift in actors' relative bargaining power (e.g., greater power shifting to development agencies). If this information signal shifts expectations about state enforcement (26, 27) or the future legal status of other PAs within the same jurisdiction then deforestation might rise within these other PAs. Thereby, when computing the impact of PADDD, such spillovers from enacted PADDD events to other PAs would preclude the use of other PAs in the same state or region as controls.

## Results

### Degazettement Risks.

***Degazettements associated with hydropower.*** Consistent with our hypothesis that a conservation-oriented agency would resist PADDD for effective PAs we find that past PA effectiveness is a statistically significant factor that predicts lower rates of degazettement. Table S4 reports our linear probability model findings using various measures of PA effectiveness: In model 1 we use the internal rate of deforestation, the nearby rate, and the interaction of the two; in model 2 we use the percent effectiveness; and in model 3 we use the binary effectiveness indicator (as defined in *Materials and Methods*).

In model 1 the PAs with lower effectiveness, as indicated by higher internal deforestation from 2001 to 2006, were more likely to be degazetted in 2010. This finding is supported by continuous and binary effectiveness metrics in models 2 and 3. The PAs that were more effective during 2001–2006 were less likely to be degazetted in 2010. Further, PA effectiveness in 2007–2009 was not a significant predictor of degazettement, likely due to the timing of decision making. One explanation is that the decision to degazette was made before the legislation authorizing PADDD was passed in 2010. The exact timing of such decisions can be hard to determine with certainty, yet evidence suggests that key legislative processes began considering the possibility of degazettement in 2006 (28).

Also, while the pressure on PAs measured by deforestation rates in a 10-km buffer around the PA did not itself predict the rate of degazettement, the interaction of the internal and nearby rates was significant. The implication is that for any given internal rate of deforestation a PA is considered more effective when the nearby rate of deforestation is higher (i.e., if more deforestation pressure is being faced and held off by the PA). We show that this higher level of effectiveness, in internal relative to external deforestation rates, made a PA less likely to be degazetted in 2010.

Finally, to set up a comparison below with the rural-settlement degazettements we also examined associations of PADDD with traditional LULCC drivers and found only one marginally significant relationship. Absence of significance was less surprising, since we had previously controlled for deforestation rates in model 1. In terms of further associations with drivers, going beyond their roles in deforestation only distance from major cities had a significant, albeit weak, effect on degazettement risk in both models 1 and 2. This suggests that the degazettement risk from hydropower does not tend to correlate perfectly with the role of urban markets' effects on deforestation pressure. We discuss this below.

***Degazettements associated with rural settlements.*** Just as for hydropower, analyses for rural settlement degazettements imply that the history of PA effectiveness is a significant factor in degazettement risk. Higher internal rates of deforestation, indicating already degraded PAs, correlate with a higher likelihood of degazettement (Table S5). In models 2 and 3, using the continuous and binary measures of percent effectiveness, results are weaker than for hydropower-related degazettements. For rural settlement PADDD events only the earliest continuous measure of effectiveness was significant [while binary metrics were not, which is likely a function of the small sample for rural-settlement degazettements ($n = 4$)].

Once again, the interaction of internal and nearby deforestation rates indicates that for any given internal rate the likelihood of degazettement is lower if the nearby deforestation rate is higher. Similar to the case of the hydropower-related degazettements, it is possible that decisions to degazette began well before the legal change itself.

Finally, looking for associations beyond the traditional LULCC drivers' roles in deforestation and controlling for deforestation, effects on rural-settlement degazettement (Table S5) are consistent with their conventional roles in tropical deforestation. Specifically, PAs that are degazetted for rural settlements tend to be closer to paved roads. Thus, PADDD for rural settlements aligns more neatly with agricultural profits than PADDD for hydropower.

***Downsize–upgrade events.*** The evolution of the Rio Sao Domingos State Sustainable Yield Forest and the Rio Vermelho B State

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Sustainable Yield Forest suggest bargaining between conservation and development agencies. In each PA one part of the PA was downsized (i.e., the area lost legal protection) while another part of the same PA was upgraded [i.e., the area gained stricter legal protection (Fig. 2)]. We hypothesized that this downsize–upgrade dynamic could occur, given variation in economic gains from PADDD (which vary with topography for hydropower) and the environmental costs of PADDD events (which can vary with effectiveness within a PA). As predicted, the upgraded lands in each of these PAs experienced far less internal deforestation than the downsized portion of each of these PAs. This may reflect an attempt at "win–win trades": Where a PA was effective protection was strengthened; however, where a PA was already ineffective protection was reversed (PADDD) to allow further development.

**Forest Impacts of Degazettement.** We did not find statistically significant impacts of PA degazettement on deforestation for either ineffective or effective PAs (see Table S6, which compares deforestation in PAs with PADDD to deforestation in surrounding areas to control for temporal trends). The absence of statistically significant impacts from the degazettement of the ineffective PAs is consistent with our hypothesis about a lack of additional effect of the PADDD itself, given that these particular PAs had already failed to effectively block nearby deforestation pressures.

Looking at the PAs that had blocked nearby pressures, this case was not capable of providing strong empirical evidence concerning the forest impacts of degazettement of effective PAs. The reason is the sample size, with only two effective PAs having been degazetted within Rondônia.

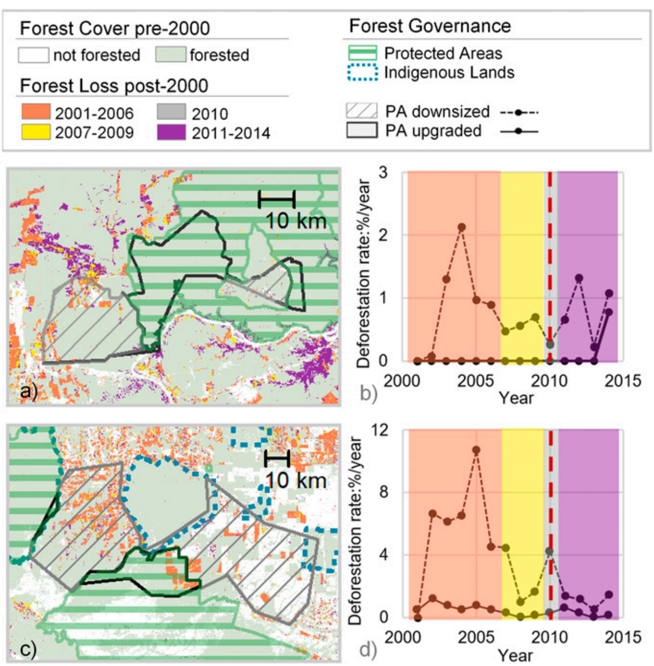


**Fig. 2.** Forest loss and deforestation rates in (*Top*) Rio Vermelho B State Sustainable Yield Forest and (*Bottom*) Rio Sao Domingos State Sustainable Yield Forest. *A* and *C* display forest loss in downsized (previously protected) lands, compared with the upgraded portion of the original PA. Forest loss corresponds to four time periods: 2001–2006 and 2007–2009 (periods before legal change), 2010 (year of legal change), and 2011–2014 (period after legal change). *B* and *D* present deforestation rates in downsized lands compared with upgraded PAs. The red dashed lines indicate when the legal change occurred.

## Discussion

**Scientific Insights and Implications.** This study contributes to the growing literatures on PADDD (11, 13, 14, 16, 24), forest governance (29, 30), and LULCC (31, 32). PADDD events in Rondônia suggest that conservation actors consider PA effectiveness when bargaining with development actors over land-use policies. PAs that were ineffective in stemming deforestation were more likely to be degazetted or downsized, whereas the PAs (or portions of PAs) that were effective were more likely to see protections maintained or, in some cases, strengthened.

Another result of this analysis is that different proximate causes of PADDD correlate with different risk factors. Even after controlling for nearby deforestation (i.e., within a 10-km buffer), as a summary of pressure, the risk of PADDD for rural settlements is related to local profitability while the risk for hydropower is not. That is logical, as development benefits of hydropower may not be located where rural agricultural profits are highest. This finding contributes to work on governance linked with drivers of LULCC, including transport costs, markets, and density of human population (9, 14). It also suggests that future analyses of PADDD risk should examine proximate causes separately. Prior work also has suggested that larger PAs, particularly in areas of higher human population densities, are more likely to experience PADDD (14). While differences in the scale and scope of analyses in this paper compared with prior research preclude direct comparison between studies, collectively these works suggest a suite of hypotheses for further testing.

Finally, the Rondônia case allowed us to examine the deforestation impacts of PADDD. As we hypothesized, we found no evidence of increased deforestation after PADDD among ineffective PAs that were PADDDed. Our finding is consistent with other research on PADDD in Brazil (16) which observed no significant impact from PADDD in the Brazilian Amazon; our work provides a more thorough empirical understanding of PADDD impacts in Brazil by exploring risks and impacts in tandem. However, these results cannot be applied to every context; earlier work (15) identified significantly accelerated deforestation due to PADDD in Peru and Peninsular Malaysia. Our conceptual framework predicts that accelerated deforestation would result from downgrading, downsizing, or degazetting effective PAs. We did not document accelerated deforestation among effective-but-PADDDed PAs in Rondônia, but our sample had little statistical power (only two effective PAs), both of which faced little deforestation pressure.

Our findings underscore the significant implications of PADDD (i.e., the impermanence of PAs) for evaluating PAs and other conservation interventions. When PAs are nonrandomly downsized or degazetted the sample of treatments (PAs) that survive are unrepresentative of the initial set of treatments (which, in turn, often are not representative of all lands). This survivorship bias likely favors effective PAs to remain protected; thus, if survivorship bias is not addressed in a study design it will likely lead to a biased (over)estimate of average PA impacts. The same issue arises for PA downgrading: Samples of the different types of PAs that are evaluated are not necessarily representative of the initial distribution of such PA types on the landscape. Hence, information about the location and the history of PADDD can inform, and improve, evaluations of PA impacts. We expect that survivorship bias may similarly affect other conservation inventions (e.g., payments for environmental services, community-based natural resource management, and ecocertification), necessitating similar methodological responses when evaluating program impacts. Future work should use available data on PADDD (12) to more holistically address the effects of initial PAs or other interventions on social and ecological outcomes.

Our findings also have substantive implications for the study of LULCC. The literature recognizes that governance significantly shapes LULCC (32), as when, for example, PA downsizing shapes rates and patterns of tropical deforestation and carbon emissions (2). Conversely, we find that LULCC shapes governance, as past deforestation shapes rates and patterns of PADDD among PAs in Rondônia. This complex and dynamic relationship between governance and LULCC in the context of PADDD suggests new directions for research on LULCC, environmental governance, and their interrelationships. Moreover, the industrial-scale resource extraction and development that follows PADDD in Rondônia (i.e., hydropower dams) and elsewhere (e.g., oil and gas, mining, and plantation forestry) raise fundamental questions regarding analyses of land availability, which may assume that PAs are permanent and inviolate (31). Although we do not observe bargaining directly, our findings are consistent with anecdotal observations suggesting that currently protected lands can become available for alternative uses through bargaining among relevant agents, (e.g., conservation and development actors), such as in the cases of Yosemite National Park and Amazon National Park (33, 34). We expect that bargaining between conservation and development actors—and, thus, the structure of environmental governance systems (e.g., PA location, size, and rules)—will be shaped by power dynamics, decision-making arrangements (35), costs and benefits of land use decisions (21, 22), the preexisting structure of property rights (17), and perhaps other factors (36). In such bargaining, lands currently available for production may become protected, as we have documented for partial PA upgrades that occurred hand-in-hand with PA downsizing (33, 34). These findings provide insights regarding LUCC dynamics and the "optimal" evolution of PA networks.

**Policy Insights and Implications.** The scientific literature has suggested procedural approaches to governing PADDD (16). Suggested policies include mandatory public consultation, social and environmental impact assessments of proposed developments, compensatory measures, and documentation and reporting of enacted and proposed PADDD events [e.g., to PADDDtracker.org and World Database of Protected Areas (11, 16)]. Our findings suggest that enhancing the ecological impacts of PAs may also enhance their legal durability. Where PADDD is impossible to avoid, conservation advocates may wish to not only negotiate to establish new PAs but also retain protection for portions of the PAs that have been effective to date and, perhaps, even upgrade or expand their protection in the bargain (22).

Recent events in Brazil highlight potential pitfalls to renegotiating PA boundaries and regulations. Past and present PADDD proposals appear to signal or create expectations regarding enforcement and the legal future of other PAs (25). Moreover, as the Rondônia case and others reveal (24), PADDD decision making can unfold over many years and reflect the dynamic bargaining positions of conservation and development actors. News reports from Brazil suggest further evolution in the bargaining power among conservation and development actors, in response to changes in political leadership and decision-making forums, resulting in the political ascendancy of development actors and a push to reduce the Brazilian conservation estate. As a result, the Brazilian government may "trade" 282,000 ha of "new" and upgraded PAs for 587,000 ha of downsizes from existing PAs (37). These accounts further illustrate bargaining over PAs and land-use policies among conservation and development actors in Brazil, with unsuccessful resolution of proposed PADDD events providing the impetus for violence (25, 33, 34).

As the Rondônia case illustrates, the complex and reciprocal relationship between PA governance and LUCC influences (and reflects) actors' behavior as they bargain over the fate of protected lands. Such dynamics likely govern the fate of other place-based conservation interventions, including community-based management of natural resources, payments for environmental services, and ecocertification programs. To ensure conservation interventions realize their full potential as a strategy for biodiversity conservation and sustainable development, and to accurately evaluate that potential, we need further understanding of environmental governance dynamics, the factors that influence them, and the fate of the lands and waters affected by them.

## Materials and Methods

Brazilian Amazon PAs have undergone considerable change since the early 2000s, providing an opportunity to explore risks and impacts of PADDD. Brazil has the largest terrestrial PA system globally, covering nearly 2.2 million km$^2$ (12.4% of the world's entire PA estate) and including globally significant areas for biodiversity and ecosystem services (16, 18, 38). Since 2010, however, PA creation has stagnated within the Brazilian Amazon and, as of 2014, 63 enacted PADDD events have affected more than 12,400 km$^2$ of protected lands and waters. Furthermore, an additional 60 PADDD events (affecting 21,000 km$^2$) have been proposed and are under consideration (16). The expansion of rural settlement frontiers (for both farming and cattle ranching) into lands that have been protected, as well as construction of hydropower dams, have been documented as the leading proximate causes of PADDD in the region (16, 18). Although we do not directly observe bargaining processes, there is anecdotal evidence of negotiated land exchanges between federal and state governments that enabled hydropower dam construction in Rondônia (19, 20).

PADDD is particularly widespread in the state of Rondônia. In 2010 alone, construction of megadams [e.g., Santo Antonio (3,150 MW) and Jirau (3,750 MW) on the Madeira River] resulted in 10 degazettements, 2 downsizes, and 2 downgrades of Rondônian PAs (16). In 2014, an additional four PAs were degazetted as (illegal) rural settlers were granted land tenure. These two "waves" of enacted PADDD events offer case studies to explore PADDD risks and forest impacts (Table S1 provides the list of PADDD events in Rondônia for the period 1980–2014, and Fig. 3 shows their corresponding locations).

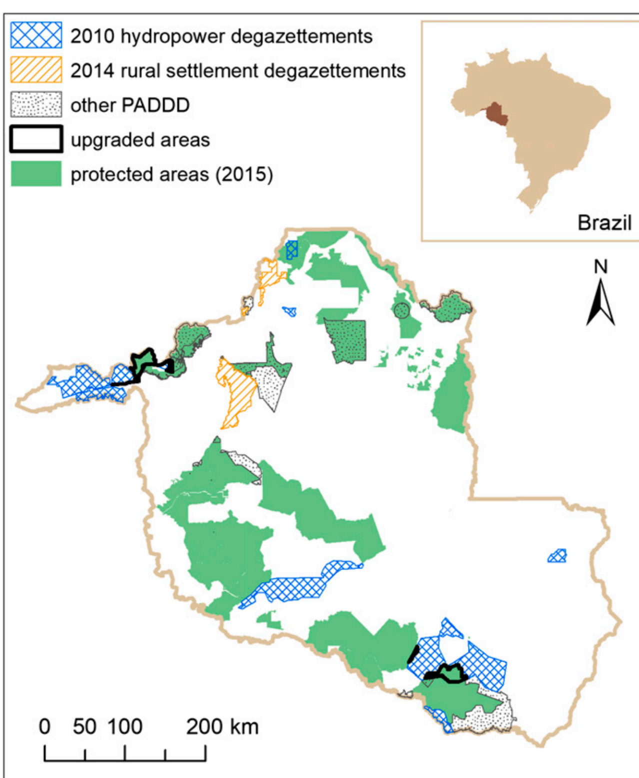


**Fig. 3.** Locations of PAs and previously protected areas in Rondônia, Brazil (1980–2014). The 2010 hydropower degazettements and 2014 rural settlement degazettements are used in the models. "Other PADDD" includes enacted PA downgrading ($n$ = 2) and downsizing ($n$ = 14) events from 1995 to 2014, associated with hydropower ($n$ = 8), rural settlements ($n$ = 2), land claims ($n$ = 1), and unknown causes ($n$ = 5).

To analyze PADDD risk for patterns consistent with bargaining, we fit linear probability regressions to study key covariates' influences on the risk of degazettement. Thus, we view the likelihood of degazettement as a linear function of factors that affect the economic benefit from the planned development as well as the perceived environmental costs. Building on prior work on PAs (9) we considered biophysical factors (e.g., slope, elevation, and distance from rivers) and socioeconomic factors (e.g., distance to major cities and roads). See Table S2 for definition and measurement of variables used in the analyses and Table S3 for descriptive statistics of these variables.

Given that ineffective PAs that are already degraded may imply lower perceived environmental costs of a PADDD event, we include the internal rate of deforestation in the PA, the nearby rate of deforestation (i.e., deforestation rates within the 10-km buffers), and their interaction term as three additional covariates. The interaction term is included because achieving a low internal rate of clearing is a stronger indicator of effectiveness if there is more pressure in the nearby areas. We also formally calculated the "effectiveness" of each PA in our sample, specifically computing percent effectiveness as deforestation in a PA relative to its nearby buffer, formally $\text{Nearby rate} - \text{Internal rate}/\text{Internal rate} \times 100\%$. We generated a categorical variable for effectiveness, which we call binary effectiveness, with a value of 1 if percent effectiveness was greater than or equal to 50%. If percent effectiveness was less than 50% the binary effectiveness took a value of 0.

Further, the Brazilian Amazon experienced high deforestation rates during 2000–2006. After this period, federal policies led to a drop in deforestation (39). Thus, for analysis of the 10 hydropower-related degazettements in 2010 we divided the period before degazettement into two periods: 2001–2006 and 2007–2009. Analogously, to analyze the four rural settlement-related degazettements that occurred in 2014 we used 2001–2006 and 2007–2013 as the two preevent time periods.

We also estimated the impacts of hydropower-related degazettements in 2010 on 2011–2014 deforestation, using 2007–2009 as a baseline. To quantify the average effect of degazettement on deforestation within sites affected by hydropower-related degazettement [i.e., the average treatment effect on the treated (ATT)] we computed a deforestation difference-in-differences [i.e., the difference between a postevent (2011–2014) deforestation difference between degazetted and nearby areas (unprotected within the 10-km buffer) and an analogous preevent (2007–2009) deforestation difference between degazetted and nearby areas]. This method, as opposed to statistical matching, is preferred for our analysis because of the limited number of treated (PADDDed) and still-protected observations.

Following our conceptual framework, we anticipate heterogeneous deforestation impacts from PA degazettement. Specifically, we expect that degazettement of historically effective PAs will have a greater impact on deforestation rates than degazettement of already degraded PAs, as the removal of protection from already degraded PAs may have minimal effect. To estimate impacts of PA degazettement more accurately, we split our hydropower-related degazettements into two groups: historically effective PAs [i.e., PAs with percent effectiveness of greater than or equal to 50% during baseline ($n = 2$) and historically ineffective PAs (i.e., PAs with percent effectiveness of less than 50% during baseline ($n = 8$)]. As described above, while allowing varied impacts, we estimate ATT for each using difference-in-differences.

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