PNAS RESEARCH ARTICLE | ECONOMIC SCIENCES
SUSTAINABILITY SCIENCE
OPEN ACCESS

Deforestation-focused policies do not reduce degradation in the Brazilian Amazon

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Edited by Eduardo S. Brondizio, Indiana University, Bloomington, IN; received April 7, 2025; accepted March 2, 2026

Forest degradation causes large declines in carbon stocks, biodiversity, and ecosystem services, despite leaving some trees standing. Over the past two decades, numerous conservation policies to halt deforestation have been rolled out, but relatively little attention has been paid to tackling degradation. More information is needed to understand how deforestation and degradation are linked and how ongoing efforts to reduce deforestation are impacting degradation. With a focus on the case of the Brazilian Amazon, a place with highly dynamic deforestation, degradation, and policy conditions, we examine the effects of four types of deforestation policies on both deforestation and anthropogenic degradation. We find that with very few exceptions, both private supply chain policies and public deforestation policy mixes that successfully reduced deforestation failed to reduce anthropogenic forest degradation. This implies that deforestation control policies alone, which are the dominant approach to the conservation of forests, are insufficient to preserve biodiversity and carbon and safeguard forest-dependent livelihoods. Policy approaches that explicitly address fire, logging, fragmentation, and other degradation drivers are urgently needed to tackle these major gaps in current conservation policy approaches. Government and companies must also include forest degradation emissions in their evaluations of current policy effectiveness toward meeting emission reduction goals.

Brazilian Amazon | forest degradation | conservation policy | supply chain policy | deforestation

Tropical forests safeguard global biodiversity and carbon stocks, and conserving these ecosystems is essential to human security and well-being (1, 2). However, these ecosystems are threatened by persistent deforestation (the complete removal of tree cover) and degradation (a state of reduced ecological functioning that does not include complete tree cover removal)—both of which threaten the well-being of forest-dependent and indigenous people living in these regions (3, 4). Between 2003 and 2014, 68.9% of net losses in carbon in tropical forests were attributable to degradation (5–7) and carbon emissions from tropical forest degradation now exceed emissions from deforestation in nearly a third of all tropical countries (8). Additionally, degradation dramatically decreases the ecosystem and biodiversity resilience to climate change (9–11) and brings local income losses, reduces access to critical community resources, and leads to numerous negative health impacts (3, 12, 13).

Degradation is particularly notable in the Amazon Basin—the world's largest remaining tropical forest. Between 1995 and 2017, 17% (1,036,800 ± 24,800 km^2) of the forest area in the Amazon basin had been degraded, accounting for 50 to 200 MT C emissions each year (3). By 2050, degradation is projected to affect the entire Brazilian Amazon (14). For comparison, 11% of the Amazon had been deforested (662,600 ± 23,100 km^2), resulting in 60 to 210 MT C (3, 15). Because of the larger extent of forest degradation, and because degradation events may occur several times on the same land, above ground biomass losses from degradation were up to three times those of deforestation between 2010 and 2019 (16), and yet the related carbon emissions were largely unaccounted for in carbon emission inventories (17). Ultimately, rising degradation, along with deforestation and climate change, limits the Amazon biome's resilience and exposes it to irreversible tipping points (18).

The causes of Amazon degradation are mostly related to droughts, fires, edge effects, logging and overhunting, and their interactions with deforestation and climate change are complex, as extensively reviewed by Lapola et al. (3). Deforestation has been found to fuel degradation by creating forest edges and isolated patches. Accounting for this degradation, the emissions associated with deforestation increase by one-third over the whole Amazon (19), and more emissions may occur from the interaction of edge effects with other degradation drivers, particularly fires (20–23).

Cattle and soy production are important contributors to degradation, both as the largest drivers of deforestation in the Amazon (directly leading to microclimate change,

Significance

We show that conservation policies in the Brazilian Amazon that have effectively reduced deforestation have failed to address forest degradation, which continues to harm carbon stocks, biodiversity, and ecosystem services. There is an urgent need for more comprehensive public and private policies that target both deforestation and degradation, including threats like fragmentation, fire, and logging, to effectively preserve the Amazon's ecological health and the livelihoods it supports.

Author contributions: F.C., F.G., S.A.L., M.S., and R.D.G. designed research; F.C. performed research; F.C. analyzed data; H.K.G. curated data; R.D.G. acquired funding; and F.C., H.K.G., F.G., S.A.L., M.S., and R.D.G. wrote the paper.

Competing interest statement: R.D.G. holds the following additional affiliations, none of which provided oversight over the content of the manuscript: Joint Committee Board, Joint Nature Conservation Committee, UK; Co-chair of the Scientific Steering Committee Member, Global Land Programme; Science Panel Member, United Nations Science Panel for the Amazon; Advisory Council Member, United Nations Forum on Sustainable Standards; Head of Science, SUMTHING; Scientific Advisory Board, RAINFOREST BUILDER; Consultant, OPM Consulting/DEFRA. H.K.G. has an ongoing consulting relationship with the nonprofit National Wildlife Federation. The National Wildlife Federation did not provide editorial oversight over the contents of the manuscript.

This article is a PNAS Direct Submission.

PNAS policy is to publish maps as provided by the authors.

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This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2507793123/-/DCSupplemental.

Published April 27, 2026.

defaunation, and biodiversity losses), as well as through increased fragmentation and fires at forest edges (3, 13, 17, 19, 21, 24–33). At the local level, the haze from fires together with the high share of land converted to pasture and crops enhance the impact of droughts by raising local temperatures and reducing rainfall (29, 34, 35), which in turn increase fragmentation and fires (36). Commodity production also stimulates local road development, immigration, and urbanization, which enhance forest accessibility (37, 38) and increases labor availability. All of these processes facilitate greater hunting (39) and logging activities, resulting in greater degradation.

Until the 5th phase of Plan for Prevention and Control of Deforestation in the Amazon (PPCDAm), beginning in 2023, there were few to no policies focused on degradation in the Amazon. Although a new integrated fire control management system is underway, up to now agricultural fire control policies have often been imperfectly implemented and were at time incongruent with local practices and the increased flammability of the landscape in a changing climate (40–42). Illegal logging is widespread (43) and, to the best of our knowledge, fragmentation remains unaddressed explicitly. Of the REDD+ initiatives deployed on the ground, only few are addressed at reducing degradation (3), and the European Deforestation Regulation (EUDR) only contemplates degradation from logging and timber production. The 2022 Science Based Targets initiative Forest, Land and Agriculture (SBTi FLAG) guidance and the Science Based Targets Network Land Targets (SBTN Land) mention forest degradation, yet we could not find publicly available evidence of companies implementing and reporting concrete actions that address forest degradation as distinct from deforestation in the Amazon. This leaves deforestation control, often focused on agricultural systems, as the primary tool currently used to achieve reduction in degradation.

To date, substantial research has examined the impacts of public and private deforestation policies on deforestation in the Brazilian Amazon. Evidence indicates that the first PPCDAm, a policy mix which included various designs and instruments at multiple scales, successfully reduced deforestation by 60 to 80% (44–49). The Priority Municipalities program (PM), a specific policy in the broader PPDCAm policy mix, which focused on credit and fiscal transfer restrictions to entire municipalities, was found to reduce deforestation by 35% (44). Other studies found that the 2006 Soy Moratorium (SoyM), a sector-wide zero-deforestation policy adopted by soy companies, reduced soy-driven deforestation by 57 to 66% (50, 51). Evidence on the deforestation impacts of bilateral agreements between state prosecutors and individual companies to remediate past harm from illegal conduct, collectively known as the Terms of Adjustment of Conducts for beef (TAC) and grains is yet inconclusive (52). In the cattle sector, the 2009 Cattle agreement (G4), also known in Brazil as the *Compromisso Público da Pecuária*, established by the four biggest meatpackers (Marfrig, Minerva, JBS, and Bertin—later purchased by JBS, all also signatories of the beef TAC) and Greenpeace to not source cattle produced on legally or illegally cleared land after 2009 was found to reduce pasture-driven deforestation by 15% (52).

Despite the widespread prevalence of forest degradation in the Brazilian Amazon and its significant impacts on carbon storage and biodiversity, no causal evaluation has been conducted to assess whether policies aimed at halting deforestation have influenced anthropogenic degradation. Addressing this question is critical, as current policies, which predominantly target deforestation, may be insufficient to mitigate forest degradation. If so, they risk failing to achieve their underlying biodiversity and carbon objectives, necessitating a reassessment of their scope to more explicitly incorporate degradation drivers. This has important implications for public policy, corporate zero-deforestation commitments, and emerging trade regulations such as the EUDR, as we return to in the discussion.

In this paper, we assess the impact of major deforestation-focused policies on deforestation and anthropogenic degradation in the Brazilian Amazon. Specifically, we distinguish between their effects on overall degradation and degradation net of deforestation—defined as degradation occurring independently of deforestation. This distinction allows us to assess whether conservation policies address degradation only through reduced deforestation or if they also indirectly affect other degradation drivers such as agricultural fire use, logging, and hunting (*SI Appendix*, Fig. S1). This is important as degradation drivers that are not directly linkable to deforestation are increasingly relevant, reducing the potential effectiveness of the policies [Fig. 1*D* and (23)]. We hypothesize that the Priority Municipality program, which increased law enforcement against environmental crimes including illegal fires and logging at the jurisdictional scale, reduced degradation beyond its direct effect on deforestation. In contrast, we expect that supply chain policies (SoyM, G4, TAC) only reduced degradation through their effect on reducing deforestation, with little additional impact on degradation net of deforestation, since degradation drivers often extend beyond property boundaries and operate at the landscape scale (3).

Our analysis focuses on the Amazonian portion of the Brazilian states of Pará, Rondônia, and Mato Grosso (Fig. 1*C*). This region encompasses a significant portion of the Amazonian “Arc of Deforestation,” where deforestation has historically been most intense in the Brazilian Amazon. Deforestation and degradation data are sourced from Vancutsem et al. (53), who defined deforestation as the clear-cutting of either intact or degraded forest and degradation as a disturbance that did not lead to clear-cutting or regrowth within at least 2.5 y. We obtain anthropogenic degradation statistically (*Methods*). We define deforestation (of both intact and degraded forest) and degradation rates as the annual rate of change relative to the previous year’s level, i.e., the amount of forest lost or degraded in year t divided by amount of forest, total or degraded, in year t−1, multiplied by 100. Fires are measured as the density per hectare of high confidence fire hotspots from Modis collection 6.1, NASA (54) and logging is recorded as the volume of timber extraction from IBGE (55) per hectare of forest.

We estimate the impact of policies using an event-study design at the municipality level, accounting for the staggered timing of policy implementation. For each cohort of municipalities undergoing a policy change in the same year, the before-after variation in outcomes is compared to that in municipalities without a policy. In this design, municipalities that are never treated or not yet treated are counterfactual for the treated municipalities under the assumption that they would have followed the same trends had there been no policy (parallel trends assumption—PTA) and that there has been no spillover across units.

1. Results

1.1. Deforestation and Degradation Coupling and Decoupling Patterns in the Study Area.

Fig. 1 describes deforestation, degradation, and their drivers in the study area across policy periods. We categorized three policy periods based on governance quality (56): emerging, peak, and retreating, the last of which was marked by progressive deregulation.

We observed that deforestation rates in degraded forests were approximately an order of magnitude higher than in intact forests

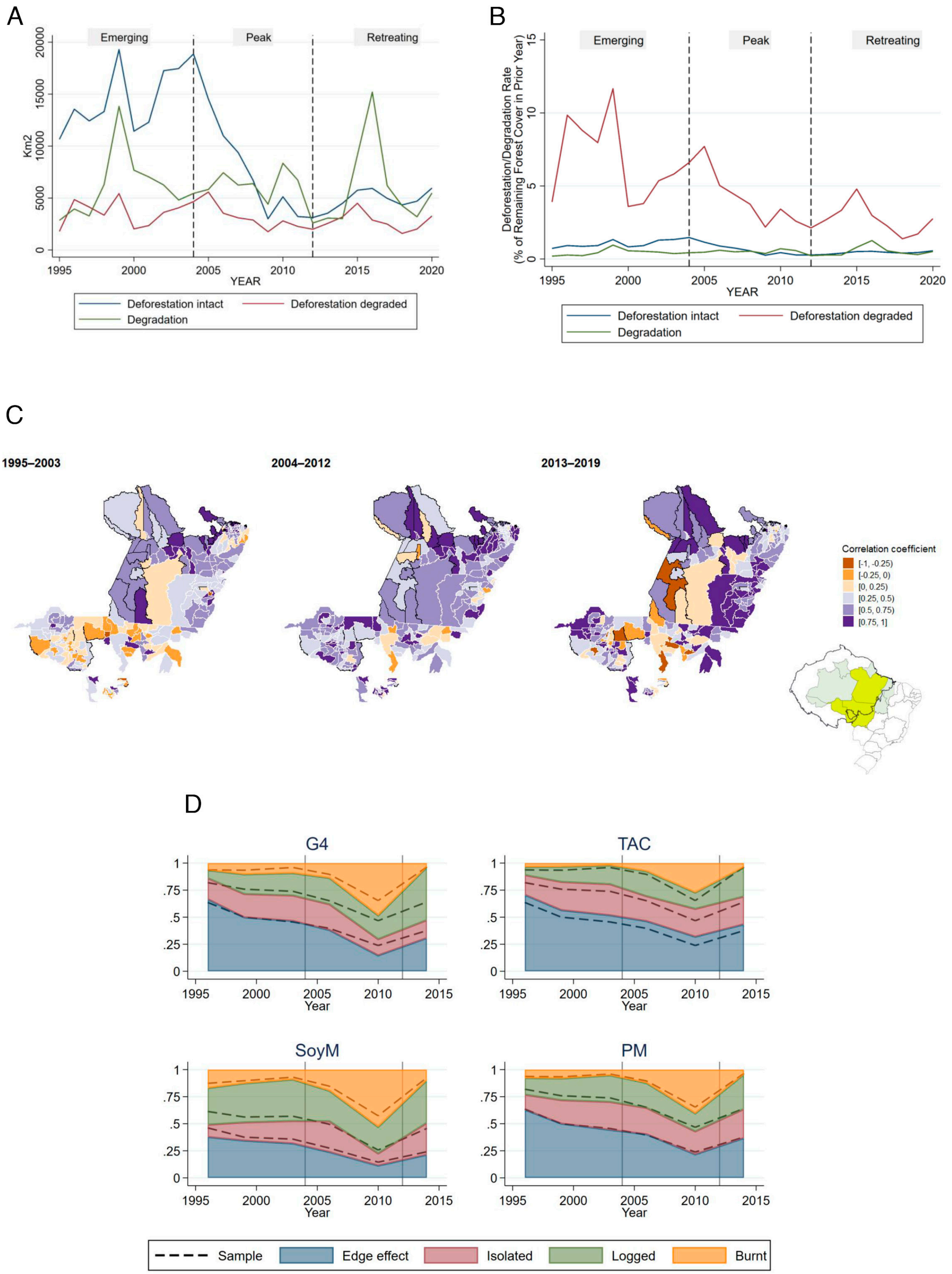

Fig. 1. Coupling and decoupling of deforestation and degradation in the study area. Panels (*A* and *B*) display degradation and deforestation trends from Vancutsem et al. (53) in the study regions, measured in km^2 and rates, respectively. Vertical lines mark three governance phases: 1) emerging, 2) peak, during the PPCDAm implementation until the deforestation minimum in 2012 (coinciding with the New Forest Code approval), and 3) the governance retreating period (2013 onward). Panel (*C*) presents within-municipality temporal correlations between deforestation and degradation rates across the three policy phases (*SI Appendix*, Table S2). Brown areas indicate negative correlations (i.e., decoupling), which are more pronounced during the peak and retreating governance periods. Municipalities with above-average deforestation have white borders, while others are outlined in black. The study area includes the Amazonian states of Pará, Rondônia, and Mato Grosso (highlighted in yellow), situated within the Amazon biome (outlined in thick black). Panel (*D*) displays the share of degraded area by degradation driver as measured by Matricardi et al. (30) for the areas that will be later exposed to the policies assessed in this paper. Dashed lines represent sample averages. The sample for the SoyM is restricted to municipalities with more than 100 ha of soy planted in 2006. Vertical lines separate the three governance periods. Values up to 2006 are prepolicy, while values for the subsequent periods include policy effects. Details on calculations are in *SI Appendix*, section S2e.

and that while deforestation in intact forests declined, deforestation in degraded forests remained relatively stable in absolute terms across governance periods. Much degradation occurred near roads and farmland (3), which were also high-risk areas for deforestation. Some deforestation may also have taken place through progressive degradation extending beyond the 2.5 y window embedded in the degradation definition of Vancutsem et al. (53). Although the total area of deforestation of degraded forest remained stable across governance periods, rates declined because degradation of intact forest exceeded the clearing of degraded forest in every year, leading to a cumulative increase in the stock of degraded forest (Fig. 1 *A* and *B*).

The relationship between deforestation and degradation fluctuated substantially across space and time (Fig. 1*C*). Evidence of decoupling of degradation and deforestation (measured via the weak or negative correlation between the two processes) was found during the peak phase, indicating that reductions in deforestation, while effective, widened the gap between deforestation and degradation because they did not reduce degradation. In the retreating-governance period, when deforestation was at its lowest, areas with below-average deforestation rates exhibited a 17% lower correlation ($P < 0.1$) between deforestation and degradation than areas with above-average deforestation (white-bordered municipalities in Fig. 1*C*; test results in *SI Appendix,* Table S2).

To distinguish driver-specific contributions to degradation, we plot the share of area degraded by each driver as detected by Matricardi et al. (30) in areas that were later exposed to policies (*SI Appendix,* section S2e). Edge effects and isolated patches can be directly associated to deforestation, whereas logging and fires are understood as only partly related. Edge effects and isolated patches consistently accounted for most degradation—both newly detected (Fig. 1*D*) and historical (*SI Appendix,* Fig. S2)—highlighting the dominant influence of deforestation. Although edge effects and isolated patches comprised nearly 80% of degradation in 1996, their contribution declined markedly over time, while logging and fire gained prominence, partly due to the substantial slowdown in deforestation between 2008 and 2012, and partly due to the 2005 and 2010 exceptional droughts. These dynamics underscore that the persistence of forest degradation as deforestation declines is at least partly related to a downshift in the relative contributions of drivers directly related to deforestation (edges and patches) and a substitution toward more degradation specific processes (fire and logging).

Finally, Fig. 1*D* shows that the distribution of degradation drivers is fairly homogeneous across areas of eventual policy exposure and relative to the overall sample, with two notable exceptions. The SoyM occurred in areas where logging and fires historically exerted a disproportionate influence compared with the rest of the sample in every period, but in line with the average in soy producing municipalities. In the last period, the role of logging is disproportionately high in areas covered by G4, as we return to in the counterfactual analysis.

1.2. Deforestation-Focused Policies Reduced Deforestation, Mostly in Intact Forests. We assess policies using an event-study design that includes cohort- and year-specific effects, yet policy impact estimates may still be confounded by selection or targeting. For example, companies adopting supply-chain policies might avoid sourcing from high-deforestation areas or prefer more productive regions that recently experienced clearing. We address these potential sources of endogeneity by lagging policy variables by 1 y, testing a range of model specifications and time periods, and restricting the counterfactual group to municipalities with similar prepolicy forest-cover levels by controlling for land-use trends. When selection is present, estimates with and without land-use trends differ and provide upper- and lower-bound estimates (*Methods*).

For each policy and outcome, we report estimates for four specifications: with and without controls and with and without land-use trends. We also present results for different time windows because policy implementation may take time, and its effects can be immediate or more gradual; policy impacts on degradation may also intensify or weaken in interaction with drought events. To remain agnostic about these dynamics, we estimate treatment effects and evaluate placebo tests for the PTA 3-y, 5-y, and full-length windows around inception (10 y for SoyM and PM, and 7 y for G4 and TAC). Fig. 2 reports coefficients standardized by the outcome's SD, which can be interpreted as changes measured in SD. Gray bars indicate the range of estimates consistent with the parallel-trends assumption; wider bars imply less reliable estimates. This instability reflects the weak policy signal relative to the high variance of the degradation outcomes. Such instability is expected because the anticipated policy effect on degradation is small or null, and degradation exhibits a SD roughly twice that of deforestation.

Both cattle supply-chain policies reduced overall deforestation. The impact of G4 remained consistent across time periods, with upper-bound estimates aligning with Levy et al. (52), whereas TAC had a significant impact only in the short term; the PTA was generally not satisfied for longer windows, consistent with selection effects reported in the literature (50). The impact of G4 was never significant in models that controlled for land-use trends, indicating that the effect was driven by comparisons among municipalities with historically different forest-cover shares (*SI Appendix,* Fig. S5). In contrast, the impact of the PM program was detected only when controlling for land-use trends and was concentrated in its early years, with effects lasting until 2016 (*SI Appendix,* Table S8). The impact of the SoyM was the most robust across specifications and time periods, although these effects were local to soy-producing municipalities (*SI Appendix,* Fig. S5).

Cattle supply-chain policies had their impact entirely in intact forests, and no model detected an effect on deforestation in degraded forests. In contrast, the PM program and the SoyM had their strongest effects in degraded forests, and the SoyM reduced deforestation in both intact and degraded forests. Its effect size was the largest and most robust across specifications.

We assessed selection effects by evaluating whether the expansion of a policy occurred over municipalities with disproportionately higher or lower historical deforestation and degradation rates (Fig. 3 and *SI Appendix,* Fig. S4). Policy expansion in areas with lower or declining historical deforestation or degradation may indicate sourcing away from noncompliant regions. Conversely, expansion in areas with higher or increasing historical deforestation or degradation may signal targeting, or sourcing directed toward more productive regions. We found no evidence of selection for SoyM or the PM because the historical outcomes remain constant over time and in line with sample average as policy expands. This may seem unexpected because the PM targeted municipalities with the highest deforestation. However, the criteria used by policymakers—total absolute deforested area, absolute deforested area in the three preceding years, and an increase in the deforestation rate in at least three of the five preceding years (Decree n. 6.321/2007)—likely led to the targeting of larger municipalities with high absolute losses rather than those with the greatest declines in forest-cover share. We found evidence of selection for TAC across all metrics, as TAC expanded over time into municipalities that had historically higher forest cover, deforestation,

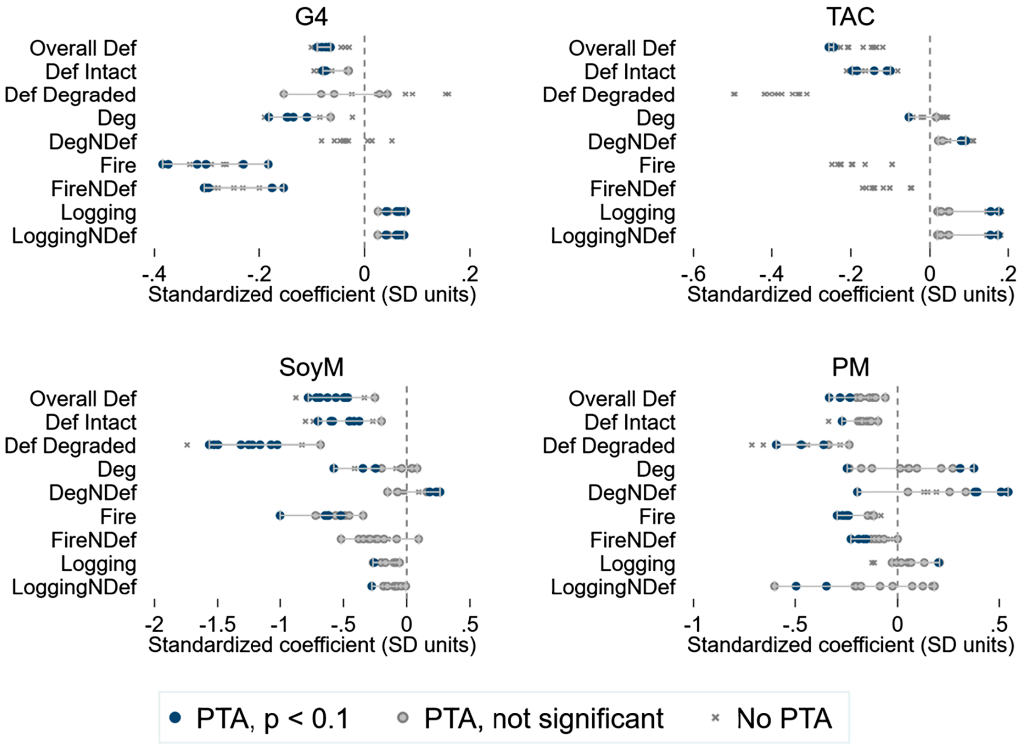

Fig. 2. Policies effects on deforestation, degradation, fires and logging across models, categorized by whether the PTA was met and the significance level. Overall def = overall deforestation; Def Intact = deforestation of intact forests; Def Degraded= deforestation of degraded forests; Det = degradation; DegNDef = degradation net of deforestation; Fire = fires; FireNDef = fires net of deforestation; Logging = logging; LoggingNDef = logging net of deforestation. PTA: Dots indicate that, for the specific model, a joint F test of placebos detects no significant differences between treatment and control groups prior to policy introduction, i.e., that the PTA is likely satisfied. Crosses indicate models for which the PTA is not satisfied and in which selection effects are likely more pronounced. Lines connect the largest and smallest estimates for each outcome among the models for which the PTA is satisfied. A more detailed description of each model results is provided in *SI Appendix*, Fig. S5.

and degradation. G4 operated in areas with higher-than-average historical deforestation and degradation and lower-than-average historical forest cover, but these characteristics remained relatively stable over time. This pattern indicated selection in levels rather than in rates of change and is consistent with the lack of robustness of the G4 effect on deforestation when controlling for land-use trends.

To further distinguish policy impacts from low-risk targeting, we compared the effect of high policy intensity with the effect of simple company presence (Fig. 4). High policy intensity (market share above 75th vs. below 50th percentiles) reflects the degree of market leverage companies can exert to enforce TAC and G4 requirements. In contrast, the presence indicator (greater than 0% market share) captures mostly sourcing selection, since minimal presence does not provide sufficient leverage to induce compliance but does reflect where companies choose to operate. If the effect estimated for high market share overlaps with the effect of presence (within their 90% CIs), then the apparent impact of the policy is compatible with low risk targeting rather than by enforcement at high intensity. If an effect appears only under high market share and not under presence, it is less likely to be attributable to sourcing selection alone. We find that the impact of G4 is likely conservative, because its expansion took place in areas with high deforestation. Although deforestation rates in G4 covered areas remained elevated, the counterfactual levels would have been even higher (Fig. 4). TAC estimates often violated the PTA for both overall deforestation and deforestation in degraded forests. However, TAC consistently reduced deforestation in intact forests, especially in the short term. The violations of the PTA for TAC, and to some extent for G4, likely reflect the fact that prosecutors initially targeted slaughterhouses most responsible for deforestation (57, 58), and possibly those located near intact areas more than those near degraded areas.

1.3. Supply Chain Policies Had No Direct Impact on Degradation beyond Deforestation Control. While all supply chain policies reduced degradation, we found no evidence that they lowered degradation independent of deforestation, i.e., after controlling for the direct effect through deforestation (Fig. 2). In the context of the observed decoupling between deforestation and degradation, this implies limited potential positive spillover to degradation.

TAC reduced degradation only in the short term, whereas G4 reduced degradation in all models with controls and across all periods (*SI Appendix*, Fig. S5), possibly as a result of pasture intensification (57). However, TAC appeared to increase degradation net of deforestation in all models that included land use trends, and G4 never satisfied the PTA for this outcome. When comparing results at high market share with company presence, we found that although the effects on overall degradation were not compatible with selection effects, the effects of TAC and G4 on degradation net of deforestation were consistent with selection effects (Fig. 4) and were therefore likely spurious. The SoyM, despite a very robust effect on deforestation, reduced degradation only in conditional models without land use trends. When controlling for deforestation, the effect became insignificant and even positive for some models.

Turning to drivers of degradation, we found that G4 but not TAC caused a reduction in fires both directly and when controlling for deforestation in models with land use trends, although this latter effect was also compatible with selection effects. G4

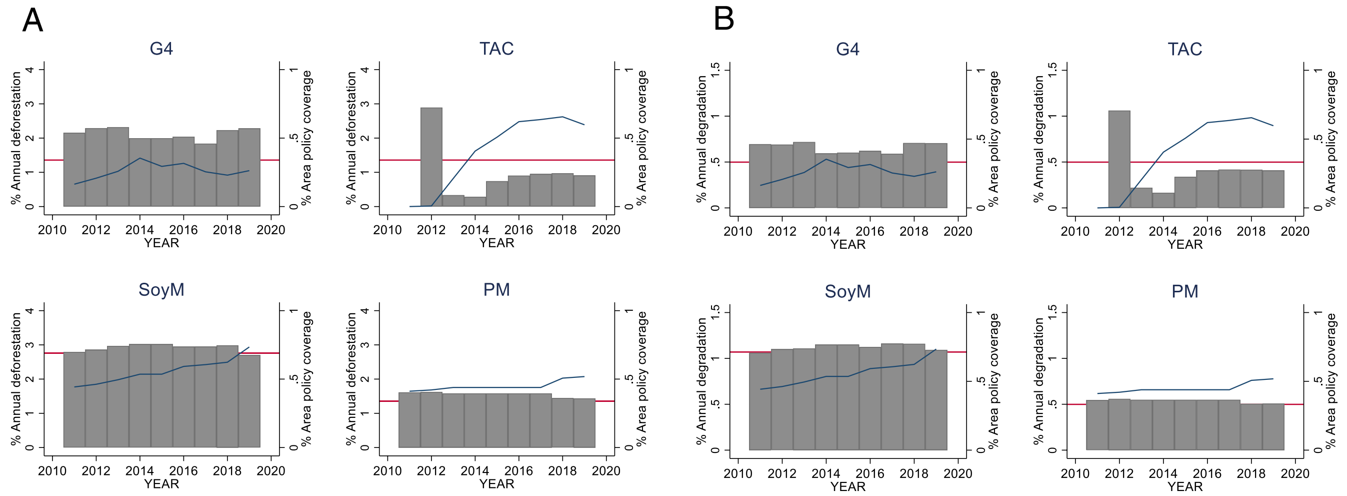

Fig. 3. Average deforestation (panel *A*) and degradation (panel *B*) rates 1996–2005 in areas covered by the policies at year t. Average degradation rate 1996–2005 in areas covered by the policies at year t. Gray bars indicate the average deforestation and degradation rates 1996–2005 in areas covered by the policies at year t. The blue line is the policy coverage level at year t indicated on the second Y axis. The horizontal red line indicates the average level of the variable on the *Left* Y axis. For the SoyM the average is computed only in municipalities producing soy in 2006.

unexpectedly increased timber extraction in a way that was not explained by selection effects (Fig. 4), possibly due to a shift in factors of production from cattle ranching to the timber sector, and this effect was robust across almost all models and time periods (*SI Appendix*, Fig. S5). Historical trajectories also showed that degradation from logging was in line with sample averages up to the introduction of G4 (Fig. 1 *C* and *D*), which ruled out selection effects from sourcing bias. The SoyM reduced fires in models that included land use trends, but the effect disappeared in all models once we controlled for deforestation. One model indicated a short-term negative effect on logging, but it appeared incidental. Given the absence of consistent impacts on fires and logging, we consider the evidence insufficient to conclude that the SoyM increased degradation independently of deforestation.

We conclude that supply chain policies reduced some degradation and fire activity related to deforestation through edge effects and isolated patches. However, none of them reduced outcomes unrelated to deforestation. Instead, we found that G4 may have spurred increased logging as a form of negative cross commodity spillover from the more to the less regulated sector (59, 60). Our finding that G4 reduced overall degradation and fires in the long term, while TAC did not, could be due to their distinct patterns of expansion into areas with varying deforestation and degradation rates, as well as the differences in the size of the companies involved and the timing and stringency of the policy efforts. Although G4 companies also signed TAC, G4 implementation began earlier, and it was found to spur cattle intensification (61), which may in turn, through mechanization and infrastructure investments, have led to lower fire use and higher fire control investments (42, 62). There is no evidence that this has happened in areas dominated by slaughterhouses that only signed TAC (63), which tended to be dominated by suppliers that are on average 42% smaller than G4 (*SI Appendix*, section S3g), and as such more likely to use fire (64). These explanations are speculative and require further exploration.

1.4. The PM Program Did Not Reduce Degradation in Average Years, but It Outperformed Counterfactual Municipalities during the 2015–2016 Drought.

The PM program, which enforced multiple environmental regulations at the jurisdictional level, reduced degradation and degradation net of deforestation in the long term but increased both in the short and medium term (Fig. 2). This contrasted with a robust negative impact on fires and fires net of deforestation in the medium and long term (Fig. 2 and *SI Appendix*, Fig. S5). However, re-estimating the PM impact by calendar year showed that the long-term reversal was largely driven by the program's strong negative effect on degradation during the 2015 to 2016 drought, 6 and 7 y after the main cohort of 30 municipalities was blacklisted (*SI Appendix*, Tables S10 and S13). We concluded that the PM program had a unique negative effect on degradation and degradation net of deforestation during the major drought years of 2015–2016. Other impacts, including those on logging, were mixed and not robust across model specifications or when re-estimating effects by calendar year (*SI Appendix*, Table S12).

2. Discussion and Policy Implications

2.1. Deforestation Control Alone Cannot Curb Degradation, Leading to Ongoing Biodiversity Loss and Carbon Emissions.

Previous studies have shown a growing decoupling of deforestation and degradation over time (15, 16, 30) alongside rising anthropogenic fires linked to droughts (65). This suggests that the drivers of deforestation and degradation differ, meaning policies effective against one may not address the other. This study provides counterfactual analysis evaluating whether deforestation-focused public and private policies also mitigated forest degradation and its drivers. While all policies reduced deforestation and, to some extent, degradation, none significantly decreased degradation net of deforestation—except for the Priority Municipality (PM) program during the 2015–2016 drought. G4 appeared to have driven higher timber extraction, possibly due to a shift in economic activity from cattle ranching to logging. The divergence in deforestation and degradation outcomes impacts underscores the risks associated with focusing narrowly on deforestation to achieve climate and conservation goals. Our results make it clear that even successful deforestation reduction policies do not automatically reduce incentives to pursue degrading activities and in some cases may even increase them—a type of negative spillover from the policy (23).

2.2. Include Degradation in Conservation Policy Goals, Targeting, and Monitoring.

We anticipated that the public PM program would curb degradation by enhancing enforcement against all types of environmental crimes and restricting credit at the jurisdictional

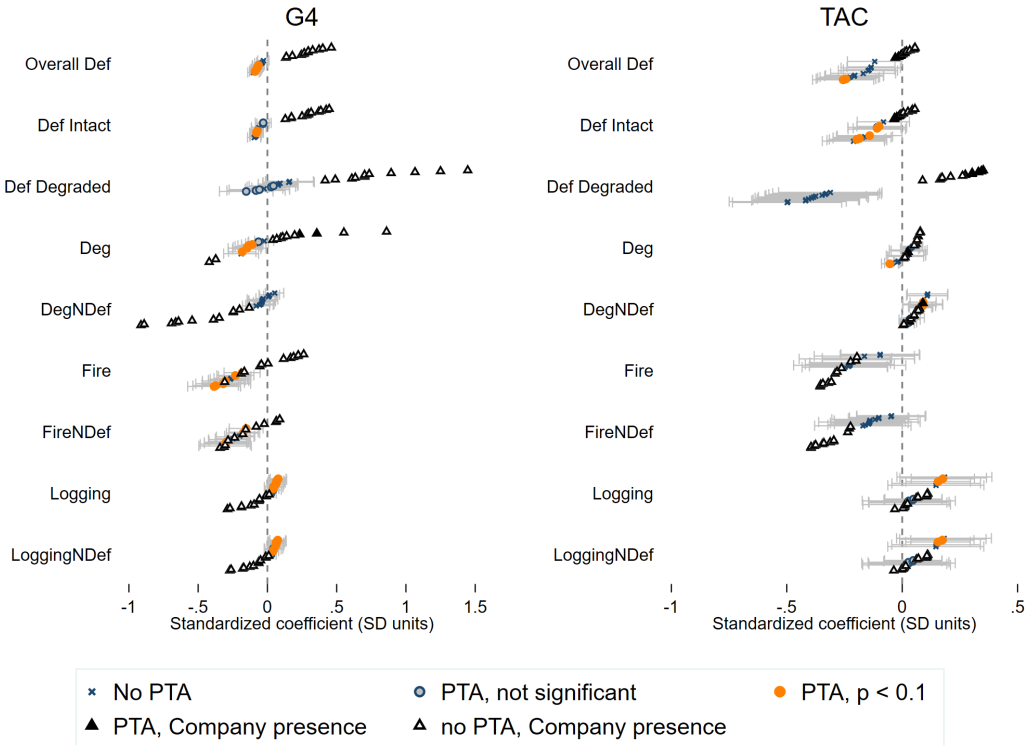

Fig. 4. Impacts of G4 and TAC changes in market share (blue dots) compared to changes in company presence (black triangles) across models, categorized by whether the PTA was met and the significance level. When the two overlap this is evidence that results are compatible with selection in sourcing behavior, rather than by changes in market share. Gray bars are 90% CI around the impacts at high market share. Overall def = overall deforestation; Def Intact = deforestation of intact forests; Def Degraded = deforestation of degraded forests; Det = degradation; DegNDef = degradation net of deforestation; Fire = fires; FireNDef = fires net of deforestation; Logging = logging; LoggingNDef = logging net of deforestation. PTA: Full and empty dots and full triangles indicate that, for the specific model, a joint F test of placebos detects no significant differences between treatment and control groups prior to policy introduction, i.e., that the PTA is likely satisfied. Crosses and empty triangles indicate models for which the PTA is not satisfied. A more detailed description of each model result is provided in *SI Appendix*, Fig. S7.

level, where degradation drivers interact more strongly than at the property level—the focus of supply chain policies. However, we find that the program only reduced degradation during the extreme drought years of 2015–2016, when annual degradation surged three and fivefold compared to 2014. While the program targeted all types of environmental crimes, municipalities were removed from the blacklist based solely on deforestation metrics.

In 2023, the PM program was updated (Decree n 11,687/2023) to include forest degradation among the criteria for inclusion and exclusion from the blacklist. According to the new regulation, municipalities exceeding 80 km^2/y of degradation will be blacklisted regardless of their deforestation performance and will need to reduce degradation to less than 40 km^2/y to exit the blacklist (MMA 983/2023).

Additionally, municipalities will receive capacity-building and resources to monitor and mitigate both deforestation and degradation, including the establishment of fire brigades (MMA 1030/2024). This is a promising development, as the underlying drivers of degradation—such as logging and fires—are complex and are best addressed at the landscape scale through cross-sectoral approaches. Moreover, by actively involving municipalities in policymaking, the program has the potential to spur substantial innovation in policy implementation (66). Notably, the degradation monitoring systems developed for this program could also be adopted by supply chain actors, enabling them to incorporate degradation into their sourcing commitments, further amplifying the program's impact.

Companies' net zero policies and associated supply chain policies and insetting efforts need to evolve to encompass forest degradation emissions and actions to curb them. This would align better with the Science Based Targets initiative Forest, Land and Agriculture (SBTi FLAG) guidance and the Science Based Targets Network Land Targets (SBTN Land) (67). Although these targets have been adopted by hundreds of companies worldwide, we were unable to identify publicly documented actions by companies operating in the Brazilian Amazon that explicitly target forest degradation. Given the high rates of degradation, companies should take concrete action against forest degradation by incorporating degradation alerts into sourcing risk assessments, and investing in monitoring of fire and fragmentation as part of traceability systems.

Finally, our findings have important implications for the EUDR and similar legislation in the United States and United Kingdom, which ban imports of commodities causing deforestation and degradation (61). The EU defines forest degradation as the conversion of primary or regenerating forests to other wooded land or planted forest and applies it only to timber products. This definition is too narrow to effectively reduce emissions from deforestation and degradation because it does not address major drivers of anthropogenic degradation in the Amazon, such as fires and fragmentation driven by soy and beef production. To more effectively address forest degradation, the EU should expand the EUDR definition of degradation, including major drivers of degradation such as fragmentation and fires, expanding the scope of forest degradation impacts beyond timber, and adopt a subnational benchmarking system that includes landscape level forest degradation (e.g., at municipality level).

2.3. Improving Deforestation Enforcement in Degraded Forests.

Our results indicated that policy-driven deforestation reductions occurred primarily in intact forests, whereas clearing in degraded forests remained more stable since the beginning of the study period. This suggests that degraded forests, which are often located near already deforested areas (20, 65, 68), remained more attractive for clearing regardless of deforestation governance. Their proximity to existing clearings likely lowered the opportunity costs of deforestation and reduced policy effectiveness. These findings indicate that further reducing deforestation in the Brazilian Amazon requires tackling persistent deforestation of degraded forests. More research is needed to understand the persistence of degradation in degraded forests and the specific drivers underlying it. As a practical implication, degraded forests should be treated as high-risk areas in company procurement and environmental governance, warranting enhanced monitoring and targeted interventions.

2.4. Tackling Fires at the Forest Edges. Agricultural fires remain an insidious challenge for both deforestation and degradation. Between 2002 and 2019, all intense forest fires detected in the Legal Amazon occurred within 0.5 km of forest edges (20). This tends to be where agricultural fields abut forests. The Forest Code bans unauthorized fire use, and prescribes control measures for authorized fires. The newly instituted Integrated Fire Management Policy (Law 14.944/2024) is a step to implement these requirements more effectively. This is promising, but landowners could be incentivized to cluster their forest reserve into contiguous areas to minimize fragmentation and edge effects, decreasing susceptibility to fires. This could be achieved through land use zoning and agglomeration incentives that reduce fragmentation within and across properties e.g., incentivizing land regularization through restoration or off-farm reserve compensation of continuous forest patches (cf. 62, 69). On the other hand, to avoid negative livelihood impacts on fire-dependent smallholders, fire risk mitigation policies must be coupled with the provision of sufficient training and equipment to adopt safe agricultural fire management practices or fire-free agricultural technologies (12), noting that fire bans alone have proven neither enforceable nor effective (63, 64).

Companies must also extend their sustainable sourcing policies requirements to exclude unauthorized and unsafe use of fire, in line with the Brazilian law (42) though this will require significant investment in monitoring data that are rapidly available for companies to incorporate into their procurement systems. Similar to deforestation criteria, a grievance mechanism should be in place to detect false positives, or when the farmer is not the liable individual (cf. 70). Stricter requirements and controls are also needed in the timber supply chain (including through PMs) to confine these activities within designated concessions and volumes (71), yet the sector has recently been deregulated, and private sectoral policies are largely insufficient (43, 72, 73).

3. Conclusion

Preserving carbon-rich and biodiverse ecosystems, as well as the people who live in them, is more critical than ever before as ecosystems throughout the world slip closer to irreversible tipping points (74). In the Brazilian Amazon, policies have primarily focused on reducing deforestation to achieve conservation goals, largely ignoring the other complex ways that humans use and impact forests (70, 75). This is problematic since growing evidence indicates that biodiversity loss and carbon emissions from large-scale forest degradation can be equally or even more significant than those from deforestation (3, 9, 11, 15, 16, 30). Moreover, these emissions are inadequately accounted for in carbon inventories and climate policies (cf. 3, 17, 19), leading to inflated carbon budgets, insufficient nationally determined contributions under the Paris Agreement, and ineffective corporate net-zero actions. Additionally, as our study shows, degradation persists even after reductions in deforestation. Consequently, policies that focus solely on deforestation are failing to fully achieve their overarching goals of preserving carbon stocks and protecting biodiversity and the broader integrity of the ecosystems essential to indigenous and traditional people's well-being.

This situation presents both a challenge and an opportunity. Targeting degradation is a complex challenge because it is the result of several interrelated drivers interacting at multiple scales and generating complex liabilities (cf. 70). Furthermore, the drivers of deforestation and degradation differ, which requires policies that address both processes while accounting for their distinct underlying causes (18). Yet there is an opportunity for conservation policy gains by integrating degradation and deforestation mitigation efforts. The opportunity costs of preventing degradation are largely limited to selective logging and game hunting, whereas protecting and restoring degraded forests can reduce fire risk and enhance the provision of nontimber forest products. Strengthening policies to address degradation offers a cost-effective and impactful pathway to improving conservation and climate outcomes. Many domestic policy changes in Brazil have been recently adopted that hold some promise for tackling degradation. The private sector and importing regions now need to follow suit.

4. Methods

We assess the impact of conservation policies on both deforestation and degradation in the Amazon and test the hypotheses that policies reducing deforestation (P1) do not significantly affect anthropogenic degradation beyond their impact on deforestation (i.e., degradation net of deforestation) (P2). An exception is expected for the PM jurisdictional policy (P3), which may influence degradation through additional mechanisms beyond deforestation control. We complement the analysis of degradation examining impacts on logging, fires, and deforestation split by intact and degraded forest. To assess P2 we run separate models for deforestation, degradation, and degradation while controlling for deforestation using a standard linear mediation procedure (76, 77). Including deforestation as a covariate isolates the policy impact on degradation that occurs independently of deforestation (solid black lines in *SI Appendix*, Fig. S1), and therefore measures the policy impact through the other channels (gray dotted lines in *SI Appendix*, Fig. S1). Conversely, omitting deforestation measures the full policy impact on degradation, including all indirect effects via deforestation (solid and dotted lines in *SI Appendix*, Fig. S1).

We define private policy treatment as a binary variable which takes value 1 if the collective sourcing market share of committed companies within a municipality is higher than a threshold (an approach laid out in refs. 50, 52, and 78). We consider relative thresholds based on the market share distribution: above vs. below 0, above vs. below the 50th percentile, and above the 75th percentile vs. below the 50th percentile for TAC and G4; and only above vs. below the 50th percentile for the SoyM, as its market share is skewed and bimodal (see ref. 50). We conduct the analysis of soy and cattle policies only in municipalities that produced soy or cattle during the study period (for the latter we only exclude the Marajó region in Pará, for which Levy et al. (52) did not provide the policy variable). To study the effects of the Brazilian government's PMs program on deforestation we use the same identification strategy employed by Assunção and Rocha (44), by comparing treated municipalities with their second-order neighbors (the neighbors of the neighbors)–thereby avoiding confoundedness from spillovers. We also do not include in the control group not-yet-treated observations, as these might experience higher deforestation rates due to targeting. The effect of the SoyM is examined from 2007 to 2019, the effect of the cattle company policies (G4 and TAC) is examined from 2010 to 2019, and the effect of the PM program is examined from 2008 to 2019.

We estimated the impact of all policies using an event study design in which municipalities are treated at different points in time or are never treated. We followed Levy et al. (52) and evaluated TAC and G4 separately because, unlike all other TAC signatories, the companies involved in G4 were much larger, committed to zero gross and not zero illegal deforestation, and started monitoring suppliers earlier. TAC and G4 market shares varied substantially over time, and therefore treatment could switch on and off several times over the study period. We used the De Chaisemartin and d'Haultfoeuille (79) and the Callaway and Sant'Anna (80) estimators, which are robust to dynamic and heterogeneous treatment effects, and the first allows treatment to switch on and off. This method relies on the assumption of pretreatment parallel trends between treated and control municipalities. However, municipalities are likely to exhibit different levels of production and productivity (81, 82). Because deforestation is a nonreversible outcome, if they had different forest cover at the start of policy implementation, they must have experienced different historical deforestation rates and trends at some point in the past. Furthermore, different land-use histories make it unlikely that deforestation-control policies were randomly assigned, which may lead to reverse causality. TAC, G4, and SoyM sourcing may be concentrated in more productive areas and farms that are already compliant, while the PM program targeted areas with higher absolute deforestation. We control for the value of cattle and soy produced each year as a proxy for productivity and lag all potentially endogenous treatment and control variables by 1 y. We further control for uneven land use history by comparing municipalities that had a similar forest cover share before the policies' introduction by controlling for a nonparametric land-use trend, i.e., interacting a categorical variable for each decile of forest cover share in 2005 with years fixed effects (the general approach is laid out in the appendix of ref. 79). The inclusion of land-use trends estimates effects within municipalities with the same deciles of 2005 forest cover share and therefore controls for selective treatment across deciles. This results into conservative estimates because it ignores genuine impacts occurring between forest cover deciles. If the effect in the base model is higher than in the model including land-use trends, most of the policy effect was likely driven by a between forest-cover decile effect. The latter may be a genuine effect, or the result of selection away from areas with more deforestation. Conversely, if the effect is higher in the model with land-use trends, this may indicate selection toward areas with higher deforestation and productivity, whereby effects between land-use deciles bias estimates upward. As such, results with and without land use trends have a bracketing property, providing a lower and upper bound estimate of the actual policy effect.

The degradation data from Vancutsem et al. (53) capture both anthropogenic drivers and natural variability. We obtain anthropogenic degradation statistically, under the assumption that natural variation in degradation due to factors that are common to treated and control units, such as climate extremes, are equally affecting treated and control units after controlling for regional variations in temperature and water balance through the Standardized Precipitation Evapotranspiration Index–SPEI (83) and initial forest stocks through nonparametric land-use trends. As a result, natural variation in degradation is accounted for through differencing in both before-after and treatment-control comparisons and the residual variation is attributed to anthropogenic activity [similar to the residual analysis proposed by Evans and Geerken (84)]. Thus, the detected policy impacts reflect changes in deforestation and anthropogenic forest degradation.

We further include controls for the value of cattle and soy produced per ha in each year, a proxy for productivity, and other policies, including the proportion of land in protected area or indigenous land. In the models for supply chain policies we also control for the number of fines as a proxy for environmental law enforcement–the latter control is omitted from the analysis of PMs, as increased enforcement is part of the program. In all models, units are weighted by the average denominator of the respective dependent variable during the study period in each municipality (i.e., forest cover or municipality area). Therefore, estimates can be interpreted as the proportion of area change (85). We test the robustness of our results by dropping all controls except for the SPEI, capturing cross-sectional variation in natural drivers of degradation. Full results are provided in *SI Appendix*, section S3f.

Data, Materials, and Software Availability. csv and dta, Stata code, metadata data have been deposited in Harvard Dataverse (86).

ACKNOWLEDGMENTS. This work contributes to the Global Land Programme (glp.earth) with the involvement of several GLP Members. F.C. and R.D.G. were supported by the European Union (European Research Council, FORESTPOLICY, #949932). M.S. was supported by the Swiss NSF Grant 218561. Views and opinions expressed are those of the authors only and do not necessarily reflect those of the European Union, the European Research Council Executive Agency, or Swiss National Science Foundation. Neither the European Union nor the granting authorities can be held responsible for them.

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