Impacts of nonstate, market-driven governance on Chilean forests

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Global markets for agricultural products, timber, and minerals are critically important drivers of deforestation. The supply chains driving land use change may also provide opportunities to halt deforestation. Market campaigns, moratoria, and certification schemes have been promoted as powerful tools to achieve conservation goals. Despite their promise, there have been few opportunities to rigorously quantify the ability of these nonstate, market-driven (NSMD) governance regimes to deliver conservation outcomes. This study analyzes the impacts of three NSMD governance systems that sought to end the conversion of natural forests to plantations in Chile at the start of the 21st century. Using a multilevel, panel dataset of land use changes in Chile, we identify the impact of participation within each of the governance regimes by implementing a series of matched difference-in-differences analyses. Taking advantage of the mosaic of different NSMD regimes adopted in Chile, we explore the relative effectiveness of different policies. NSMD governance regimes reduced deforestation on participating properties by 2–23%. The NSMD governance regimes we studied included collaborative and confrontational strategies between environmental and industry stakeholders. We find that the more collaborative governance systems studied achieved better environmental performance than more confrontational approaches. Whereas many government conservation programs have targeted regions with little likelihood of conversion, we demonstrate that NSMD governance has the potential to alter behavior on high-deforestation properties.

deforestation | timber | certification | program evaluation | supply chains

Since the 1980s, production of commodities for distant markets has emerged as a dominant driver of deforestation (1–3). As the relative importance of global, rather than local, demand for agricultural and forest products has grown, transnational corporations have become critical actors in influencing land use change. In response, various nonstate, market-driven (NSMD) governance regimes have emerged to improve the environmental and social impacts of commodity production (4–6). Such NSMD governance systems are the result of complex interactions between corporations and nongovernmental organizations (NGOs) (7). These systems take a variety of forms including multistakeholder agreements, land conversion moratoria, and ecocertification schemes. Although voluntary in nature, they derive authority through markets. Credible threats of market exclusion, or promises of price premiums can serve to incentivize more responsible social and environmental practices (8). Such governance structures have been praised for their potential to slow deforestation associated with the production of Brazilian soy and beef (9), Indonesian palm oil (10), and boreal timber (11).

Despite the growing optimism surrounding these NSMD governance regimes, questions remain about their effectiveness in achieving environmental outcomes. For example, environmental benefits may be limited if the producers opting into ecocertification are those already meeting sustainability standards (12). Although direct conversion of forests to soy production in the Brazilian Amazon dropped precipitously after the implementation of the soy moratorium (13), indirect land use changes may have displaced soy expansion, causing deforestation elsewhere (14). The costs of compliance with NSMD regimes may exceed the benefits for landowners, minimizing the potential for large-scale conservation benefits (15). In addition, suppliers may be able to circumvent environmental agreements by segmenting markets and shipping production that fails to meet environmental standards to consumers with weaker environmental concerns (16). Even if initially effective, corporate commitments to environmental practices may wane as public attention turns elsewhere (17).

Such critiques highlight the importance of clear program evaluation to determine the effectiveness of NSMD governance regimes. Most ex-post evaluations of NSMD governance in the forestry sector have focused on the legitimacy of the decision-making process rather than on the environmental outcomes of the regime (18). Clear assessments of the environmental impacts of this new form of environmental governance are lacking (8, 16, 19, 20), due in part to the short history of NSMD governance and confounding effects of broader market dynamics and government policies (9). Previous assessments generally failed to meet basic standards of rigor such as comparison with a credible control (21). Recently, a handful of studies have begun to provide more rigorous assessments of the impacts of NSMD governance on deforestation. These studies indicate that Brazil's zero deforestation cattle agreement (22) and forest certification in Indonesia (23) have reduced rates of deforestation, whereas timber certification in Mexico (24) has had insignificant impacts on deforestation.

Beyond identifying the effectiveness of any one NSMD regime, a comparison of the impacts of different approaches to environmental governance is essential to improve policy design. As with traditional governance systems, NSMD interventions can vary at any of the traditional stages of the regulatory process:

Significance

Global trade in commodities has become an important driver of environmental degradation. In response, there has been a proliferation of nonstate, market-driven governance seeking to reduce environmental degradation through interventions in the supply chain. We provide some of the first quasiexperimental evidence to show that private, market-driven policies can slow deforestation. We compare the impacts of two certification schemes and a deforestation moratorium in Chile using a factorial quasiexperimental design. Our results indicate that governance regimes with greater collaboration between environmental and industry stakeholders achieved better environmental outcomes. In contrast to many public conservation policies, we find that private governance systems can effectively target high-deforestation properties.

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agenda setting/negotiation, implementation, and monitoring/enforcement (25). In the first stage, NGOs must decide how to balance confrontational and collaborative strategies (26). Similarly, industry participants can choose the level of collaboration with which to respond; either participating in multistakeholder negotiations or developing their own standards to compete for legitimacy (4). In both cases, the balance between collaboration and confrontation may shift during the latter stages of the regulatory process. Cooperation in regulatory processes has been found to improve the environmental performance of public policies (27, 28), but relatively little is known about the impact of collaboration on the effectiveness of private governance regimes.

In a policy ecosystem with multiple NSMD governance regimes, individual policies may interact in complex ways. Interactions can be direct (e.g., an individual property owner adopts multiple NSMD governance regimes simultaneously) or indirect (e.g., competition between NSMD governance regimes lead to changes in NSMD governance adoption or rules). Both direct and indirect interactions can affect the outcomes associated with any individual policy as different governance regimes can complement, substitute, or weaken the effectiveness of individual policies (16). As a result, it is important to understand how stacked NSMD governance regimes may differ in their outcomes from individual interventions that are implemented in isolation.

This study addresses three questions: Can NSMD governance regimes achieve conservation outcomes? How do NSMD governance regimes with varying levels of collaboration between stakeholders differ in their effectiveness? Do interacting governance regimes complement, substitute, or weaken individual policies? We use quasiexperimental methods and data on property-level land use change in Chile to assess the impacts of a mosaic of different NSMD governance regimes.

Chile's forestry sector provides a rich history of NSMD governance. By the end of the 20th century, the conversion of natural forests to industrial pine and eucalyptus plantations had become the primary cause of Chilean deforestation (29, 30). Efforts to improve management of natural forests through traditional government policies were often halted. Chile's native forest law spent 15 years in Parliament before being adopted in 2007—longer than any law in Chilean history (31). In response to growing demands from US retailers for more sustainable products, several quasigovernmental agencies worked with the primary forestry trade association to develop El Sistema Chileno de Certificación de Manejo Forestal Sustentable (CERTFOR), a national certification for sustainable forest management that was later endorsed by the Program for the Endorsement of Forest Certification (PEFC). Although the two largest Chilean forestry corporations [Arauco and Compañía Manufacturera de Papeles y Cartones (CMPC)] pursued CERTFOR certification for the majority of their subsidiaries, other corporations began to certify their operations through the Forest Stewardship Council (FSC). The competition between FSC and the producer-backed CERTFOR standard mirrored global discussions about the relative stringency of forest certification standards defined by an industrial sector (as for CERTFOR) or by multistakeholder initiatives where other stakeholders such as environmental NGOs have a strong voice (as for FSC) (20).

As the Chilean corporations began to negotiate and adopt certification standards, many NGOs launched confrontational campaigns to pressure the Chilean corporations to reform (32). In advertisements in the *New York Times*, the environmental NGO ForestEthics encouraged American consumers of Chilean timber to demand an end to forest substitution and to only purchase Chilean timber certified by FSC.* As a result of increasing consumer pressure, the Home Depot helped convene a series of meetings between environmental NGOs, and the Chilean forestry corporations CMPC and Arauco. In 2003, CMPC, Arauco, the Home Depot, and 10 environmental NGOs reached an agreement they referred to as the Joint Solutions Project (JSP), whereby Chilean timber corporations committed not to clear natural forests on their properties.† In 2007, an additional agreement was reached with a third corporation, MASISA, bringing the total share of plantations owned by JSP participants to 64% (33).‡

Although the conditions that gave rise to the three NSMD regimes (CERTFOR, FSC, and JSP) were different, the substance of the forest conversion commitments in each standard were roughly similar. All three policies explicitly prohibited the future conversion of natural forests to plantations† (34, 35) and called for transparency in the form of monitoring by third parties. Each policy included some incentive for compliance, whether in the form of an end to negative publicity in the case of the JSP or access to differential labeling in the case of FSC or CERTFOR certification. One of the few previous comparisons of FSC and CERTFOR found that participants in the two certification schemes introduced similar numbers of institutional changes (36). However, differences in the policies did exist. The JSP included explicit language prohibiting companies from encouraging forest conversion by other property owners. FSC standards went beyond the other two policies by retroactively punishing past substitution through restrictions on the certification of any plantations established on lands that had been natural forests before 1994. Mirroring a global debate about the relative rigor of corporate versus multistakeholder certification schemes (4, 37), many environmental groups expressed concern that the corporate CERTFOR standard was environmentally inferior to the FSC standards (38).

Chilean implementation of the JSP, FSC certification, and CERTFOR certification provides a unique opportunity for the quasiexperimental evaluation of the impacts of NSMD governance. All three policies included a common and clearly observable objective—to halt conversion of natural forests to plantations—by which to judge their effectiveness. Despite widespread public discourse about the merits of the different programs (38, 39), there has been no rigorous quantification of their environmental impacts. Fortunately, the different governance regimes were adopted nearly simultaneously but heterogeneously across the country, allowing for their comparison and the analysis of their interactions (Fig. 1). Finally, rigorous quasiexperimental quantification of these effects was enabled by the relatively long time period since policy adoption, as well as by available data on land use change, and property boundaries and ownership.

Results

At the start of our study period, the sample properties covered 329 thousand hectares of natural forests and 478 thousand hectares of plantation forests. Over the following 25 years, a net deforestation rate of 1.38% per year led to a net loss of 97 thousand hectares of natural forests. In contrast, plantation forests expanded at an annual rate of 2.30%, adding 367 thousand hectares. Between 1986 and 2011, property owners converted 38% of their natural forests to plantations. Across the study properties, the average gross rate of conversion of natural forests to plantations was 2.35% per year during the first time period (1986–2001), dropping to 2.11% during the second time period (2001–2011), but varying by NSMD participation (Fig. 2).

Propensity score models highlighted observable differences in the characteristics of properties participating in each of the different treatments (Tables S1–S3). Potential plantation rents were positively correlated with the likelihood to participate in any of the

*ForestEthics (September 13, 2002) Your dream home in a small clearing in the woods. *NY Times*. Advertisement.

†CMPC Maderas S.A., et al. (2003) Memorandum of understanding.

‡Masisa, ForestEthics (2007) Memorandum of understanding.

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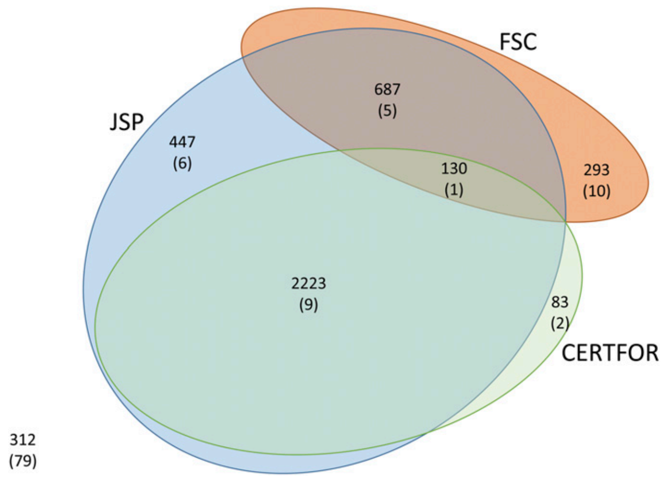

Fig. 1. Number of properties (companies) in each NSMD governance regime.

three NSMD regimes. In addition, properties participating in NSMD governance regimes were generally located closer to markets. They also had higher initial proportions of land dedicated to plantations, more land in the highest land capability classes, and higher pretreatment rates of forest substitution. The multiscale model emphasized that larger companies were more likely to be participants in NSMD governance. Finally, multiple comparisons across the different treatment groups (Table S2, h, j, m, and o) underscored the fact that properties with FSC certification tended to have lower historical rates of deforestation than properties pursuing other NSMD governance regimes.

Using matched difference-in-differences, we estimated the average treatment effect on the treated (ATT), a measure of the gain from the intervention, of each NSMD governance regime (Table S4 and Fig. 3). Pooled together, the ATT on properties governed by any of the three policies ("any policy" group) was a reduction in forest substitution of 0.338 ± 0.294 percentage points (g). This decrease is equal to a 2–23% reduction in the annual rate of forest conversion. Although this result was not significant in the alternate specification of this model using cluster robust SEs ($P = 0.17$), it was moderately significant ($P = 0.10$) in the spatial lag model with cluster-robust SEs. The effectiveness of the any-policy treatment was further supported in the multilevel model that explicitly accounted for company-level covariates (x). Although only estimated on the small subset of the overall sample falling on the common support (*Supporting Information*), this model found significant impacts ($P \leq 0.01$) in all three model specifications.

Of the individual assessments, the JSP only (a, -0.508 ± 0.304) and FSC only (b, -0.870 ± 0.373) treatments demonstrated significant reductions in forest substitution rates. No treatments exhibited significant increases in the rate of forest substitution (a–f). Both of these results were evident in all three model specifications.

Paired comparisons between treatment groups were used to evaluate the relative effectiveness of different policies. FSC certification had a greater effect than either JSP participation (h) or CERTFOR certification (m) alone, or the adoption of both the JSP and CERTFOR certification (o). Although all three of these results were evident in the main model and the alternate cluster-robust specification, the spatial lag model yielded less significant differences between FSC certification and (*i*) the JSP-only treatment (h), and (*ii*) the JSP and CERTFOR treatment (o). However, the spatial lag model did indicate that joint implementation of FSC, CERTFOR, and the JSP may have generated greater reductions in forest conversion than implementation of only CERTFOR and the JSP (v). Finally, the comparison between properties adopting only CERTFOR certification and those participating only in the JSP found that the JSP was more effective in reducing forest conversion (i).

Paired comparisons between properties participating in multiple, overlapping governance regimes tended to emphasize a lack of synergy and the possibility of interference between governance regimes. Comparing properties with stacked governance regimes to properties with only some of the same governance regimes tended to find null or counterintuitive results. In the models without a spatial lag, properties participating only in FSC certification demonstrated greater reductions in forest conversion than those participating in both FSC and the JSP (n). Although only significant in a few specifications, our analysis indicated that properties participating only in the JSP may have achieved greater reductions in forest conversion than properties participating in both the JSP and CERTFOR (k), or the JSP and FSC (j). Even in the case where multiple policies did achieve more reductions than properties with a subset of governance regimes (v, spatial lag specification), the stacked treatment effect was less than the additive effects of the individual treatment effects from each policy. We found no evidence that adoption of NSMD governance resulted in leakage to proximate properties. Changes in forest conversion rates on properties without NSMD governance were comparable whether or not those properties were located in close proximity to NSMD participants (s).

Discussion

Our results show that NSMD governance regimes can slow deforestation. Between 1986 and 2011, 124 thousand hectares of natural forests in the studied properties were converted to plantations. The different NSMD interventions reduced annual rates of forest conversion by 2–23% compared with the no-policy counterfactuals. In aggregate, these policies conserved 3.82 thousand hectares of natural forests. Although NSMD governance reduced deforestation, all three programs sought to end, rather than reduce, the rate of forest substitution. In this context, anything short of 100% reductions in deforestation within NSMD properties could be interpreted as noncompliance with the governance regimes. However, because our treatment time period included several years before the implementation of the NSMD governance regimes, our analysis would tend to underestimate compliance. In addition, given the voluntary nature of the governance regimes, any significant reductions in forest conversion could be viewed as a policy success.

During their initial negotiation and adoption, the JSP, FSC, and CERTFOR governance regimes varied in the level of engagement and confrontation between industry and environmental interests.

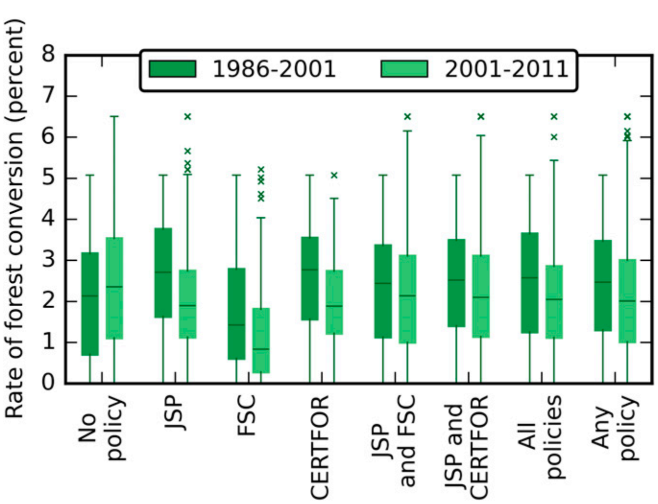

Fig. 2. Unmatched comparison of forest conversion rates by policy.

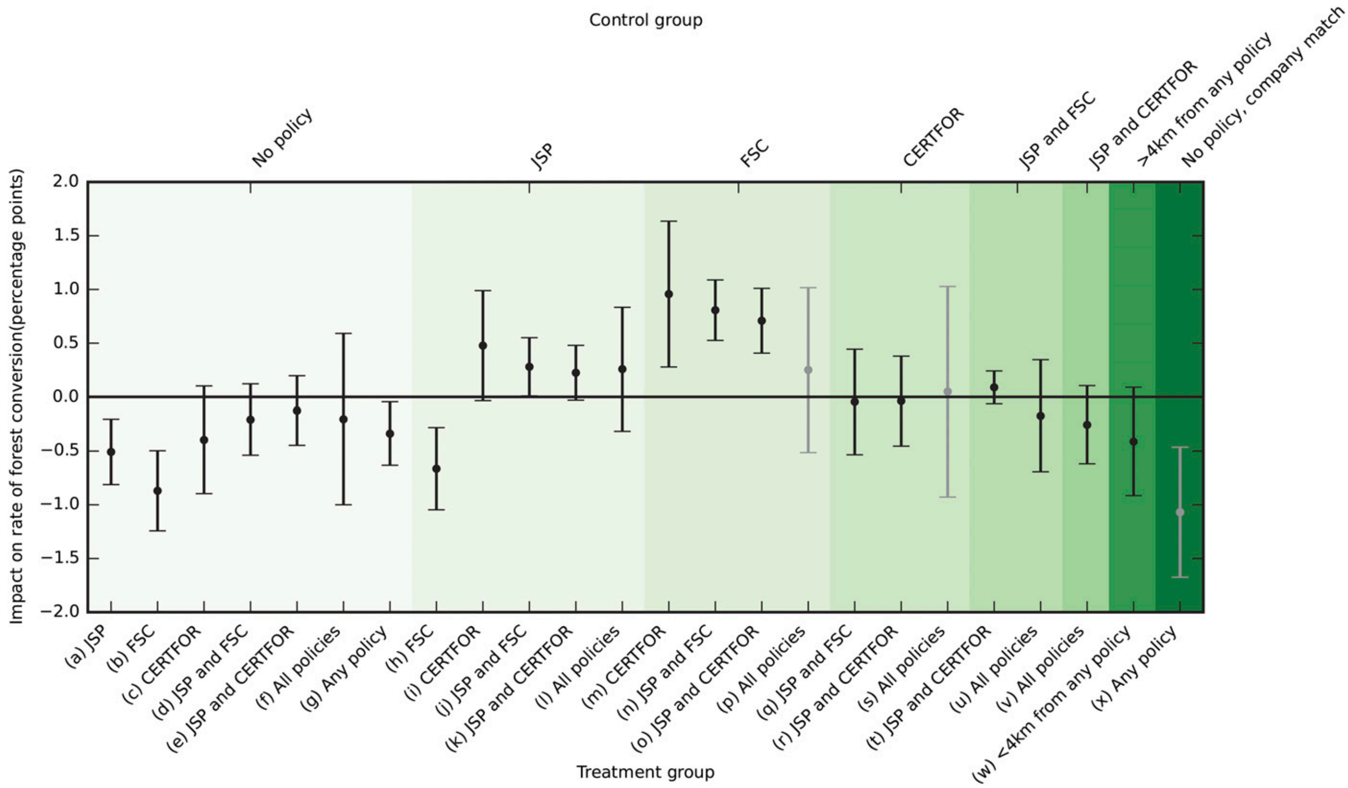

Fig. 3. Comparisons of treatment effects estimated through matched difference-in-differences. Gray bars indicate that propensity score matching failed to achieve acceptable balancing across all covariates. Error bars represent 95% confidence interval using propensity score robust SEs.

As the product of multistakeholder negotiations, FSC certification represented the most collaborative governance regime (40). Nearly all of the companies certified by FSC in its first 5 years of operation in Chile actively participated in the rule-making process for the development of FSC's Chilean standards. In contrast, the CERTFOR certification scheme sought to demonstrate that industry could self-regulate, without participation from civil society. Given their exclusion from the CERTFOR standard-setting process, several NGOs expressed concern over the certification scheme's environmental rigor (38). Finally, the JSP was developed through a combination of confrontational and collaborative strategies. Initially instigated through negative publicity by NGOs, industry and NGO interests eventually collaborated to develop the JSP's commonly agreed-upon standards.

Our results indicate that FSC certification was more effective in slowing forest conversion than either the more industry-friendly CERTFOR standard or the JSP moratorium. Furthermore, the CERTFOR certification standard, which arguably had the least engagement between companies and civil society, was the least effective NSMD policy. Clear identification of a causal relationship between collaboration and environmental performance is complicated by the fact that the choice between collaboration and confrontation is rarely binary. In most cases, actors shift their level of collaboration in different stages of the regulatory process, or different actors may simultaneously adopt different strategies. Given this nuance and the small number of governance regimes analyzed, we are unable to claim a causal link between collaboration and environmental performance. Nevertheless, our results are consistent with theoretical (41) and empirical results (27, 28) indicating that more collaborative forms of governance can lead to better environmental outcomes.

In assessing interactive effects of different policies, we found no evidence to suggest that combining multiple governance regimes on a single property would improve environmental performance. In several cases, properties adopting multiple NSMD regimes exhibited worse environmental performance than properties adopting only one of the constituent regimes. One possible explanation for this outcome would be interference across the different policy regimes. In addition to the direct property-level interactions measured by our quasiexperimental methods, the different NSMD governance regimes also interacted in important ways at the national scale. The existence of FSC certification may have increased the rigor of environmental safeguards in the final CERTFOR standards. Although initial external assessments of CERTFOR noted weak protections of natural forests (42), the final CERTFOR plantation standards included clear language to limit natural forest conversion (35). Second, the NGO campaign that led to the adoption of the JSP may have also accelerated the adoption of FSC certification. The initial market campaign encouraged consumers to purchase only FSC-certified Chilean timber. Arauco and CMPC, the primary targets of the NGO campaign, initially supported the development of the CERTFOR standard as an alternative to FSC. However, after continued NGO criticism of the CERTFOR standard, both companies pursued FSC certification. These interactions at the national level reinforced two existing theories on the adoption of NSMD regimes: (*i*) competition between NSMD governance regimes can strengthen industry-led standards; and (*ii*) NGO campaigns can encourage the adoption of environmental certification (20, 37).

Differences in the implementation of NSMD governance seemed to align with differences in the types of properties affected. Early adopters of FSC had to be willing to collaborate with environmental NGOs and sought to differentiate their products based on environmental performance. In practice, FSC properties tended to have lower rates of pretreatment forest conversion than other plantation properties. In contrast, the JSP was initiated as a campaign to reform behavior. In this case, NGOs targeted specific corporations that they viewed as priorities for reform. High pretreatment rates of forest conversion were a strong indicator of participation within the JSP (Table S2). These differences emphasize a potential strength of NSMD governance regimes. Although protected areas and other public conservation policies have the potential to nearly eliminate deforestation, such interventions typically target regions with relatively low rates of deforestation (43, 44). In contrast to conservation areas located in inaccessible locations, the properties affected by NSMD governance belonged to Chile's largest timber corporations. The pretreatment rate of net deforestation on NSMD properties was 1.83%, more than double the rate of net deforestation across all of central Chile (0.83%). In addition, the properties participating in NSMD governance had higher than average potential rents for plantation forestry.

Theory indicates that the adoption of NSMD governance could lead to multiple forms of spillovers affecting rates of forest conversion on nonparticipating properties. Restrictions on conversion could increase demand for land suitable for plantation forestry, increasing conversion of natural forests on nonparticipating properties. To address such concerns, timber companies participating in the JSP agreed not to undertake actions that would encourage the conversion of natural forests on properties outside their direct control. Ideally, an analysis of the resulting leakage patterns would look at leakage as a process mediated by supply chains and corporate relationships in addition to purely spatial lags. We posit that both the potential negative effects of indirect land use change, and the potential positive effects from policy spillovers would have the strongest impact near participating properties. However, we find minimal leakage from NSMD properties to proximate properties. In addition to market-mediated leakage, environmental campaigns and negotiations that led to NSMD governance may have encouraged broader policy reforms and changes in norms across the entire sector. Such reforms would have more wide-reaching positive effects but are difficult to isolate given the structure of our analysis.

Conclusion

Using quasiexperimental methods, we demonstrated that Chile's NSMD governance regimes were successful in reducing natural forest conversion to plantations by 2–23%. Of the three governance regimes evaluated, the multistakeholder FSC certification standard achieved better environmental performance than either the industry-led CERTFOR standard, or NGO-incited JSP moratorium. In contrast to traditional public conservation policies such as protected areas, these NSMD governance regimes were often implemented on properties with high historical rates of deforestation. Although our case study was focused on Chile, the analysis can provide insights to guide the rapid spread of NSMD governance globally. First, NSMD policies can achieve real improvements in environmental performance despite their voluntary nature. Although compliance with NSMD governance is often less than that achieved through public conservation efforts such as national parks, NSMD policies tend to do a better job in targeting high-deforestation properties. As a result, NSMD governance may serve as a useful complement to traditional, government policies. Finally, greater collaboration between environmental and industry interests in establishing NSMD standards is likely to improve the environmental performance of the resulting policies.

Methods

We sought to measure the impact of NSMD governance in Chile's forestry sector on the rate of natural forest conversion to plantations. To do so, we (*i*) developed a hierarchical dataset identifying properties owned by timber companies and the subset of those properties affected by each NSMD governance regime; (*ii*) calculated the rate of natural forest conversion in pretreatment and posttreatment time periods for each property; and (*iii*) conducted a series of matched difference-in-differences analyses to measure the effect of each policy. We provide a summary of these methods below and a more thorough description in *Supporting Information*.

Sample Selection. To link outcomes to treatment adoption and other associated covariates, we developed a multilevel dataset spanning pixels, properties, subsidiary companies, and their parent corporations. We used government cadastral data to link unstructured spatial data to property boundaries and the names of property owners. We then restricted our study to the set of properties owned by forestry companies. Individual companies were associated with parent corporations using market and corporate reports. By combining this ownership information with primary data sources such as certification records and signed voluntary agreements, we identified properties participating in NSMD governance. Finally, we sorted the properties into eight groups representing properties regulated by the following: JSP only, FSC only, CERTFOR only, JSP and FSC, JSP and CERTFOR, all three programs simultaneously, any of the three programs, and none of the three programs.

Calculation of Natural Forest Conversion. Our outcome variable of interest was the rate at which natural forests were converted to plantation forests within each property. We calculated this rate using land use change maps from ref. 45. For each property, we calculated the annualized rate at which natural forests were converted to plantations during each of the two time periods.

Matched Difference-in-Differences. We measured the average effect of NSMD governance on the rate of forest conversion within properties participating in NSMD governance (ATT) through the use of a series of matched difference-in-differences analyses. For our primary results, we defined our treatment group as those properties participating in any NSMD governance regime, and our control as those properties participating in no NSMD governance regime. We used a biophysical, geographic, and economic controls to preprocess our samples using propensity score matching. Diagnostics indicated that the matching procedure reduced observed differences between treatment and control groups (Fig. S1 and Table S3).

We took advantage of our longitudinal data to control for unobserved, time-invariant characteristics of the properties such as company ownership. We calculated the difference-in-differences estimator of the ATT, adjusting SEs to reflect the estimated propensity scores (46). The benefits of combining matching with panel methods have been confirmed through design replication studies comparing quasiexperimental results to the results generated from random controlled trials (47, 48). Very few studies have used this two-staged analysis for the identification of the effect of policies intended to slow deforestation (49, 50), and even fewer have used this method to measure the impact of NSMD governance of land use (23, 24).

We repeated this process to compare the relative effectiveness of different programs, and to test for complementarities across programs as outlined in ref. 51. For each of the possible pairwise comparisons between the different groups, we assigned one group to the treatment, and the other group to the control. Iterating through all of the possible combinations, and including comparisons to test for spatial leakage and a multilevel specification, we were left with 24 pairwise comparisons for analysis.

To test the robustness of our results, we ran two alternate specifications of each quasiexperiment, and two additional quasiexperiments. First, to account for within-company correlation of errors, we reran all models using company-level cluster-robust SEs. To test robustness to observed spatial autocorrelation, we reran all models with spatially lagged dependent variables. Although our primary models emphasized property-level characteristics, we explored the robustness of our results through a multilevel model that incorporated company-level covariates. Finally, we tested for leakage by comparing forest conversion on proximate, untreated properties to untreated properties located more than 4 km from the nearest property participating in NSMD governance.

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Supporting Information

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SI Methods

Our objective was to determine the average treatment effect of the JSP, FSC certification, and CERTFOR certification on the properties participating in each of the programs [average treatment effect on the treated (ATT)] as well as their relative and interactive effects. We used a combination of propensity score matching and panel methods. Matching techniques have been widely used within the environmental program evaluation literature as a way to create a counterfactual control that resembles the treatment group on a variety of observable variables (12, 19). However, matching alone requires strong assumptions that there are no unobserved variables that are associated with both the treatment and the outcome variables.

Panel methods, in which repeated observations are made on each unit, have been promoted for their ability to control for time-invariant but unobservable sources of confounding. The difficulty in collecting the necessary data to conduct panel analysis has limited their use in conservation program evaluation (12). Recent increases in the availability of fine-resolution, global-scale time series on deforestation is creating new opportunities to implement this method (52).

Increasingly, there is recognition that the most robust quasiexperimental estimation strategies combine matching and panel techniques (48, 53, 54). Preprocessing data through propensity score matching improves the robustness of causal inference to parametric model misspecification, yielding a "doubly robust" estimation strategy (53). The benefits of combining matching with panel methods have been confirmed through design replication studies comparing quasiexperimental results to the results generated from random controlled trials (47, 48). Very few studies have used this two-staged analysis for the identification of the effect of policies intended to slow deforestation (23, 24, 49, 50).

Study Area. Our study area comprised the central part of Chile spanning from the Valparaiso region in the North, to the Los Lagos Region in the South. This region was selected based on the availability of consistent, high-resolution data on land use change (45). Although these data do not enable a full, national-scale analysis, the studied regions include 99% of Chile's plantation forests (55). Additionally, more remote regions were not included in the government property cadaster and land use quality datasets and thus had to be dropped from the analysis (56). Because we observed little plantation expansion in these regions, we felt that their exclusion would have little effect on the substantive results of the analysis.

Scale of Analysis. We developed a hierarchical view of land use change spanning pixels, properties, subsidiary companies, and their parent corporations. At the finest scale, remotely sensed, 30-m pixels described land use change at a high resolution across the entire study area. Such unstructured data have served as the foundation for many previous analyses of the impacts of policies on land use decision making (57).

Although remotely sensed data have led to a proliferation of pixel-level analyses, such studies abstract from the underlying processes driving land use change by ignoring ownership patterns. Recently, land use change analysis has made increasing use of data on property boundaries to better reflect the scale at which land use decisions are made (22). We aggregated pixel-level observations to patterns on individual properties using a set of regional cadasters developed between 1996 and 2001 (56). The full dataset included information on the spatial boundaries and the name of each owner for 292,708 properties within our study area. Although we lacked data on changes in property boundaries or ownership of individual properties, our dataset spanned the middle of our study period. Given the long investment times necessary for profitable forest management, we believe that our property data should be valid for the 25-year duration of our study period.

Although properties better represent decision making than individual pixels, ownership patterns in many rural landscapes reflect a system in which one owner may control multiple individual properties. In such cases, additional aggregation may be necessary to best reflect the true scale of decision making. Using owner names associated with each property, we aggregated individual properties to the set of all properties owned by a single company. To ensure valid comparisons, we used property owner names to constrain our sample to only include properties owned by timber companies. We were unable to account for properties owned by individuals who either rent or sell to larger companies. To identify timber companies, we created a list of the names of the largest timber companies based on government and market reports (33, 58). In addition, we included all property owners with names that included common forestry sector keywords "forestal," "bosques," and "madera." Due to naming inconsistencies and spelling errors within the cadaster, we used the fuzzywuzzy fuzzy string matching package for Python to compare the names of property owners within our dataset to our list of timber companies. Our sample pool included all properties whose owner name had a token set ratio similarity to a timber company name of at least 90%. Our final sample included 4,175 properties belonging to 112 companies.

In many cases, individual companies can be further aggregated to their parent corporations. For example, at the end of our study period, the holdings of Chile's largest timber corporation, Arauco, included Forestal Celco, Forestal Cholguán, Bosques Arauco, Forestal Valdivia, Forestal Los Lagos, Forestal Bío Bío, and Forestal Viñales among others. We identified subsidiaries of larger corporations based on corporate financial reports, as well as ref. 33. We relied upon corporate financial reports and market news services to track mergers and acquisitions across the study period.

The hierarchical nature of our data introduced opportunities and challenges in the estimation of the effects of NSMD governance. Given the role of site-specific characteristics (e.g., land quality, distance to markets, historical land use) in driving land use change, we chose to focus our attention on patterns of forest conversion within individual properties. We incorporated our hierarchical ownership data to precisely identify the properties affected by the different NSMD governance regimes. In the case of the JSP, adoption occurred at the level of the largest, parent corporations. As a result, it was necessary to link parent companies to the individual properties to most accurately assign the treatment. In contrast, forest certification generally occurred at the scale of individual subsidiaries. In this case, it was necessary to separate the individual subsidiaries to know which properties were affected. Despite these benefits of our hierarchical data, the use of individual properties as the unit of observation introduced potential complications for the econometric estimation of the effects of NSMD governance. We address these challenges in *Robustness to Scale* below.

Treatment Specification. We identified the properties participating in the JSP by selecting all properties that belonged to CMPC, Arauco, MASISA, or one of their subsidiaries by 2007. To identify the properties governed by FSC or CERTFOR, we compiled lists of all of the forestry companies that had begun certification in

Chile under one of the two regimes by 2007. These lists were based on existing reviews as well as the certification databases of CERTFOR and FSC (39).

Factorial Analysis. Heterogeneity in the adoption of JSP, FSC, and CERTFOR NSMD regimes led to a nearly factorial configuration of the different possible combinations of the three programs. For our primary analysis, we compared properties that were regulated by any NSMD governance regime to those properties that participated in none of the regimes. However, to evaluate the independent, relative, and interactive effects of each of the different NSMD governance regimes, we used a series of conditional binary selection models considering the different possible combinations of policies (51). This framework allows for comparisons of each policy to the untreated population to generate clear effect sizes for each treatment. In addition, pairwise comparisons between the different treatment groups allow for assessments of the relative impacts of different treatments. Finally, comparison of combined policy treatments to individual policy treatments can help elucidate the interaction effects of different policy interventions.

A full factorial combination of our three different policies would allow for eight different groups—no treatment, JSP only, FSC only, CERTFOR only, JSP and FSC, JSP and CERTFOR, FSC and CERTFOR, and all policies. However, we found no properties that participated in both FSC and CERTFOR but not the JSP. As a result, we were left with seven groups to compare, yielding 21 different possible comparisons. Table S1 summarizes the sample size and summary characteristics of each of the different groups. After including the primary analysis comparing any NSMD regime to a no-policy control, an alternate specification of this comparison with corporate-level covariates and a separate comparison with test for leakage (discussed below), we were left with 24 different comparisons.

Outcome Variable. Chile's NSMD governance programs sought to achieve a variety of objectives. These included social goals such as the recognition of indigenous and worker's rights, as well as environmental goals including soil conservation, responsible use of chemicals, and biodiversity protection. Of these objectives, we chose to focus our analysis on "forest substitution," the conversion of native forests to plantations. We emphasized this outcome due to three considerations. First, forest substitution has been a particularly important point of discussion in the Chilean public discourse and academic literature (29, 45). Also, in contrast to other environmental objectives such as soil conservation, forest health, or chemical additions, forest substitution presents a clear outcome that can be comprehensively and consistently measured across the entire study area. Finally, elimination of forest substitution was the one common objective of the JSP, FSC, and CERTFOR, and thus allows for clear comparisons across NSMD programs.

In the case of the JSP, ending forest substitution was the primary goal of the program.[†] Both the FSC and CERTFOR included specific criteria that restricted forest substitution (34, 35). These criteria were maintained throughout all versions of the standards used over the course of the study period. In addition to these criteria, CERTFOR and FSC certification reports give further evidence of their emphasis on ending forest substitution. One early adopter of FSC was unable to certify specific holdings due to evidence of forest substitution (59). In both the FSC and CERTFOR, certification proceedings uncovered nonconformities pertaining to forest substitution and mandated corrective actions (60, 61). More recently, many companies seeking FSC certification have had to respond to detailed external reports cataloging all instances of forest substitution (62, 63).

To measure the effectiveness of these regimes in halting conversion of natural forests to plantations, we calculated the annualized rate of native forests conversion to plantations ($r_{i,t}$), for each property (i), over each of two time periods, 1986–2001 and 2001–2011 (t) as given by Eq. **S1**:

$$r_{i,t} = \left(1 + \frac{c_{i,t}}{f_{i,t}}\right)^{\frac{1}{l_t}} - 1. \qquad \textbf{[S1]}$$

Land use change maps from ref. 45 were used to calculate the area of forests converted to plantations ($c_{i,t}$) and the area of forests at the start of each period ($f_{i,t}$). We used annualized rates because the length of our two time periods (l_t) were not the same. Although the NSMD regimes did not go into effect immediately upon the start of our treatment period, they did govern land use changes over the majority of this period.

Propensity Score Matching. To evaluate the independent, relative, and interactive effects of each of our treatments, we used a series of conditional binary selection models (51). This framework allows for pairwise comparisons of different treatment groups and the untreated population to generate clear effect sizes for each treatment. In addition, pairwise comparisons between the different treatment groups allow for assessments of the relative impacts of different treatments. Finally, comparison of combined policy treatments to individual policy treatments can help elucidate the interaction effects of different policy interventions.

To conduct our match, we chose to apply a 10:1 nearest-neighbor matching algorithm. Due to the small number of controls for some of our comparisons, we chose to use replacement in our nearest neighbor selection. We applied a caliper (0.005) to minimize the bias introduced by poor matches (54, 64). Given the caliper, we felt more confident in oversampling ($n \leq 10$) to achieve greater precision in our estimates while not introducing too much additional bias (64). We adjusted SEs to take into account the fact that our propensity scores are estimated rather than known (65). Because we sought to estimate the ATT, we verified that all of the treatment properties fell within the support created by the controls (64). In some cases, we were forced to trim our treatment sample to the common support. Although this increases the validity of our estimates for the final sample group, it does introduce a new risk that the estimated effect sizes might not be representative for all treatment properties.

To assess the quality of the matches, we compared the balance of covariates across our treatment and control groups before and after matching. We used the normalized difference in means rather than t test comparisons to assess the quality of balance (Table S3) (54). In our final results (Table S4 and Fig. 3), we indicate which experiments failed to yield a postmatching normalized difference for each covariate below the rule of thumb (0.25) noted in ref. 54. In addition, we evaluated quantile–quantile (QQ) plots comparing the distribution of treatment properties to control properties for each continuous covariate before and after matching. The QQ plots for each of our matched experiments are presented in Fig. S1 (53). The final propensity score models for each experiment are presented in Table S2.

Model Covariates. We followed three guiding principles from the matching literature in selecting covariates for our models of propensity scores. First, we aimed to select variables that simultaneously affect treatment participation as well as the outcome of interest (53, 64). Based on the scientific literature, we identified variables that have been shown to affect land use decisions, and are also likely to differ systematically between properties owned by the different plantation companies (1). These include economic variables such as the distance to markets, biophysical variables such as the land capability class, and geographic variables such as the total area of the property. Second, we avoided the use of variables that may be affected by participation—either directly or through anticipatory behavior (64). Many of our variables (e.g., slope, elevation, area) are fixed and thus unaffected by participation. For variables that change over time, we chose to match only on the variable value from the beginning of the study period (1986), long before any discussion of the JSP had begun. Finally, we followed refs. 47 and 66, and erred on the side of inclusiveness over model parsimony. A summary of the included covariates by treatment is presented in Table S1.

Most of the variables used were directly taken from existing sources as referenced in Table S1. The exceptions included our outcome variable (described above) and our estimate of potential plantation rents. Plantation rents were calculated using the

$$
\begin{aligned}
R_{f,i,t} &= \frac{NFV_{f,i,t}}{(1+r)^{A-1}} NFV_{f,i,t} = \sum_{y=0}^{A} V_{y,f,i,t}(1+r)^{A-y},\\
R_{f,i,t} &= \text{Net present value of rents to plantation type } f,\\
&\quad\ \text{for plot } i, \text{ at time } t,\\
NFV_{f,i,t} &= \text{Net forest value of all cash flows of a rotation of}\\
&\quad\ \text{length } A \text{ in a plantation of type } f, \text{ at plot } i, \text{ at time } t,\\
V_{y,f,i,t} &= \text{Value of cash flow in rotation year } y, \text{ in a plantation}\\
&\quad\ \text{of type } f, \text{ for plot } i, \text{ at time } t,\\
r &= \text{Discount rate.}
\end{aligned}
\tag{S2}
$$

Faustmann formula for the net present value of forest income: Separate models were developed for pine lumber, pine pulp, and eucalyptus pulp plantations. We combined these three models by calculating weighted averages for each region based upon the local share of plantation area by species, and the local share of pine logs by use (pulp or lumber) (58).

Timber yields were calculated for each of the three plantation types, within each of 10 growing regions using the EUCASIM and RADIATA forest models (67). Average prices for each of the plantation products (pine pulpwood, pine saw wood, eucalyptus pulpwood) over each of the two time periods were calculated using data from government quarterly price reports (68). Official estimates of plantation establishment costs were averaged over each of seven macroregions to generate estimates of the initial investment cost (69). Additional plantation management practices and their associated costs were based off of government plantation rent models (70). We used forestry sector shipping costs from an econometric analysis of Chilean freight prices (71).

Difference-in-Differences. To control for unobserved, time-invariant characteristics, we took advantage of our longitudinal data and used a difference-in-differences estimator. Following ref. 46, we modified the traditional difference-in-differences estimator to incorporate the preestimation matching described above:

$$\tau = \sum_{i \in T} \left(\left(r_{it} - r_{it'}\right) - \sum_{j \in C} w_{ij} \left(r_{jt} - r_{jt'}\right) \right). \tag{S3}$$

τ is the average treatment effect on the treated. r is the rate of forest conversion as defined in Eq. **S1**. t' indicates the pretreatment time period, whereas t indicates the posttreatment time period. T is the set of properties receiving treatment during period t. C is the set of properties in the control group. w_{ij} is the weight given to control property j compared with treatment property i. Given the property-level differencing in the outcome variable, the estimator will be robust to any time-invariant, property-level sources of variation in the outcome variable.

Robustness to Scale. Although the use of individual properties as the unit of observation allowed for better controls of site-specific drivers of forest conversion, it introduced two potential problems for the econometric estimation of the effects of NSMD governance. First, our estimation of treatment effects was based upon the assumption that our property-level observations were independent. However, common ownership of multiple properties may undermine this assumption and lead to biased estimates of model SEs. To address this concern, we reran the model using cluster-robust SEs, clustered at the scale of individual companies. Given that many of the comparisons in our factorial design included only a few clusters, caution should be used in interpreting these results (72). In presenting the significance of our cluster-robust results, we accounted for the small number of clusters by comparing our estimates to a T(G − 1) distribution where G is the number of companies. We are unaware of a rigorous econometric approach to simultaneously adjust for clustering and the fact that propensity scores were estimated in the first stage of the analysis. As a result, we present both SEs that adjust for propensity score estimation and the cluster-robust SEs in Table S4.

Second, because participation in NSMD governance was decided at the level of entire companies, company affiliation and associated characteristics may better explain the uptake of NSMD governance than property-level attributes. For example, ref. 73 found that company-level trade exposure was a strong determinant of NSMD adoption in the Canadian timber sector. A propensity score estimator that ignores the multilevel structure of the underlying data may fail to fully control for selection biases underlying the adoption of the treatment (74).

The most rigorous way to address this source of bias would be to adopt a multilevel model in which company-level variables, random effects, or fixed effects are added to both the propensity score and outcome models (75). In our setting, however, multilevel propensity score models may be "too good" at predicting treatment due to the scale at which NSMD policies were adopted (64, 76). Because all properties belonging to a company were exposed to identical NSMD governance treatments, company-level fixed and random effects would perfectly identify treatment assignment. Similarly, the inclusion of company-level covariates may act as an indicator of treatment assignment. Because many of the comparisons within our factorial design compared properties from only a handful of companies against each other, the inclusion of multiple company-level covariates generated propensity score models that perfectly predicted treatment assignment. In response, we limited the use of the multilevel propensity score model to our pooled comparison of properties belonging to companies with any NSMD governance to the no-policy controls. To generate our multilevel model, we modified the model underpinning experiment g by adding aggregate company-level covariates to both the propensity score estimation and difference-in-differences model. These covariates included the total area of a company's properties, their average slope, elevation and aspect, the area-weighted average plantation rents, and the share of all of a company's property in the different starting land uses and land quality classes. The resulting model perfectly identified treatment assignment on the majority of treatment properties, leaving only a small fraction of treated properties on the common support. Because we limit our analysis to observations on the common support, our estimated ATT is thus only valid for this limited subset (64).

Although within-company homogeneity in treatment assignment limited our ability to apply the multilevel propensity score model to all of the experiments in our factorial design, our second-stage difference-in-differences analysis did implicitly account for the hierarchical nature of the underlying data. Simulation studies have emphasized the increased consistency of doubly robust estimators that take into account multilevel structure in at least one stage of the analysis. In particular, ref. 75 finds that accounting for the multilevel structure of data through the inclusion of cluster-level random or fixed effects in the second-stage outcome model can dramatically reduce the bias of propensity score weighting estimators. Consistent with these findings, we use a doubly robust, matched difference-in-differences model for all our ATT estimates. As discussed in the previous section, this difference-in-differences estimator controls for the time-invariant characteristics of a property, including membership in higher organizational levels. Our base model thus acts as a reparameterization of the doubly robust, cluster-level fixed-effects model proposed by ref. 75.

Spatial Autocorrelation. To test for spatial correlation in our dependent variable we calculated Moran's i. The results indicated significant clustering in the rate of forest conversion. In response, we chose to run additional robustness checks using a spatial lag model. We calculated the spatial weights (W_t) across observations using an inverse distance model implemented using PySAL (77). We lagged our dependent variable (r) based on this weighted matrix. To account for the lagged dependent variable in the estimation of the ATT, we calculated the difference-in-differences across matched properties (M) using a spatially lagged regression with fixed effects for the time period (P), the group of treated properties (T), and their interactions. The resulting estimation equation is given in Eq. **S4**. The coefficient (τ) on the interaction between treatment time period and treatment property ($T_i \times P_t$) yields the ATT estimate. The results from the spatial lag model are presented in Table S4.

$$r_{it} = M_i(\rho W_t r + \beta_0 + \beta_1 T_i + \beta_2 P_t + \tau(T_i \times P_t)) + \mu. \qquad \textbf{[S4]}$$

Leakage. We implemented an additional test for local leakage to explore spillovers resulting from the adoption of NSMD governance (43). We divided the properties that never participated in any of the three NSMD governance regimes into two groups: a treatment group of properties that were located within 4 km of a NSMD participant, and a control group composed of properties located more than 4 km away. As with our other comparisons, we calculated the ATT using a matched difference-in-differences estimator.

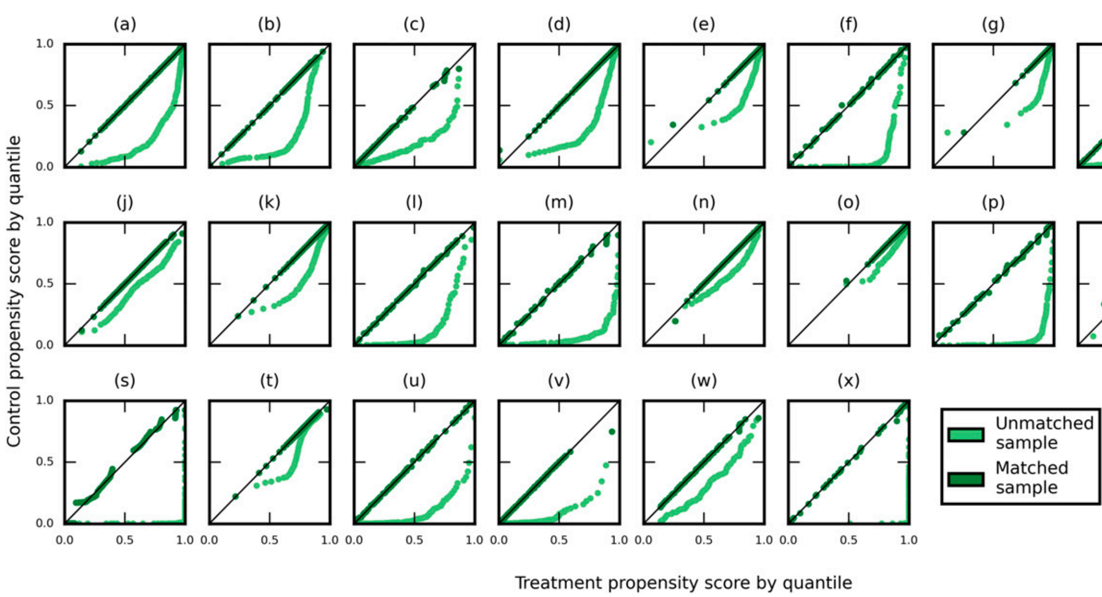

Fig. S1. Quantile–quantile plots comparing propensity scores of treatment to control properties before (light green) and after (dark green) matching. Each panel represents one of the 24 quasiexperiments and is labeled with a letter (*A*–*X*) representing the relevant column in Table S4.

Table S1. Summary of property characteristics by treatment

Variable	Units	Data source	No policy	JSP	FSC	CERTFOR	JSP and FSC	JSP and CERTFOR	All policies
Proportion agriculture in 1986	Percent	Heilmayr, 2015 (45)	0.23	0.31	0.34	0.17	0.35	0.26	0.59
Proportion plantation in 1986	Percent	Heilmayr, 2015 (45)	0.25	0.3	0.19	0.46	0.24	0.32	0.18
Proportion forest in 1986	Percent	Heilmayr, 2015 (45)	0.24	0.25	0.26	0.17	0.23	0.23	0.07
Proportion shrub in 1986	Percent	Heilmayr, 2015 (45)	0.26	0.13	0.21	0.21	0.16	0.18	0.15
Proportion moderate land quality	Percent	CIREN, 2001 (56)	0.15	0.1	0.12	0.13	0.09	0.1	0.34
Proportion low land quality	Percent	CIREN, 2001 (56)	0.79	0.67	0.81	0.84	0.73	0.83	0.5
Property size	ha	CIREN, 2001 (56)	436	296	233	300	227	300	547
Elevation	m	USGS, 2008 (78)	348	443	265	353	338	320	291
Slope	Degrees	USGS, 2008 (78)	8.48	7.97	8.74	9.92	7.2	8.45	3.48
Distance to urban area	km	CIREN, 2001 (56)	33.98	27.24	25.03	34.93	25.96	26.7	16.8
Plantation rents	Million CHP/y	See discussion in *SI Methods*	1.12	1.35	1.43	1.27	1.36	1.34	1.32
Pretreatment rate of forest conversion	Percent/y	See discussion in *SI Methods*	2.06	2.64	1.74	2.56	2.25	2.44	2.47
Posttreatment rate of forest conversion	Percent/y	See discussion in *SI Methods*	2.35	2.02	1.16	2.01	2.16	2.21	2.27
Properties	*n*	CIREN, 2001 (56)	312	447	293	83	687	2,223	130
Unique companies	*n*	See discussion in *SI Methods*	79	6	10	2	5	9	1

Table S2. Propensity score models

				Proportion agriculture in 1986		Proportion plantation in 1986		Proportion forest in 1986		Proportion shrub in 1986		Proportion moderate land quality		Proportion low land quality		Property size		Elevation		Slope		Plantation rents		Distance to urban area		Pre-treatment rate of forest conversion		Constant		*N*
				Percent		Percent		Percent		Percent		Percent		Percent		ha		Thousand m		Degrees		Million CHP/year		km		Percent/year				
Label	Treatment	Control	Scale of covariate	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error	
(a)	JSP	No policy	Property	6.249*	3.519	7.543**	3.510	3.347	3.532	3.600	3.565	−2.930***	0.578	−1.876***	0.482	−0.485***	0.144	3.702***	0.620	0.0124	0.0176	3.378***	0.478	−0.00184	0.00643	22.81***	7.314	−9.270***	3.524	732
(b)	FSC	No policy	Property	4.599	2.885	3.490	2.903	4.786	2.981	2.783	2.959	−0.884	0.692	0.375	0.606	−0.580***	0.191	−3.239***	0.670	0.00533	0.0186	3.441***	0.459	0.00234	0.00773	−9.980	7.895	−7.361**	2.861	591
(c)	CERTFOR	No policy	Property	47.65**	23.07	50.78**	23.00	44.87*	23.05	48.85**	23.16	0.183	1.421	0.239	1.344	−0.190	0.243	2.192**	0.921	0.00121	0.0259	2.753***	0.589	0.0202**	0.00849	4.251	11.60	−54.52**	22.91	383
(d)	JSP and FSC	No policy	Property	3.950**	1.987	3.711*	1.985	2.172	2.027	1.438	2.031	−3.248***	0.567	−1.394***	0.466	−0.240*	0.131	−0.603	0.488	−0.0358**	0.0153	3.702***	0.439	0.00179	0.00601	8.069	6.563	−4.918**	2.078	975
(e)	JSP and CERTFOR	No policy	Property	0.217	1.267	0.926	1.243	−0.739	1.261	−1.980	1.260	−1.261**	0.496	0.0120	0.419	−0.197**	0.0805	−0.561	0.403	−0.00564	0.0129	2.772***	0.296	−0.00823*	0.00496	16.28***	5.145	−0.833	1.345	2,464
(f)	All policies	No policy	Property	0.967	2.620	0.591	2.685	−9.416***	3.134	−1.539	2.722	0.509	0.871	−0.628	0.891	0.446***	0.139	4.283***	1.317	−0.223***	0.0555	4.498***	0.891	−0.0193	0.0171	19.26*	11.09	−5.598*	2.907	420
(g)	Any policy	No policy	Property	1.465	1.195	1.442	1.170	0.171	1.189	−1.308	1.185	−2.049***	0.469	−0.669*	0.405	−0.123**	0.0577	−0.219	0.378	−0.00928	0.0121	2.431***	0.245	−0.0138***	0.00443	11.89**	4.901	0.0791	1.270	4,060
(h)	FSC	JSP	Property	−3.884	4.499	−6.371	4.523	−0.255	4.529	−2.975	4.547	1.811***	0.615	2.537***	0.453	−0.203	0.251	−8.077***	0.819	−0.0262	0.0185	1.836***	0.480	−0.00738	0.00891	−33.20***	7.718	2.428	4.446	721
(i)	CERTFOR	JSP	Property	48.92*	27.70	51.41*	27.61	47.69*	27.62	53.40*	27.69	4.090***	1.402	2.806**	1.233	−0.444	0.292	−2.462***	0.934	0.0161	0.0235	−1.082*	0.572	0.0366***	0.00920	−18.94	11.63	−52.87*	27.43	513
(j)	JSP and FSC	JSP	Property	−0.634	3.581	−1.782	3.568	−0.0232	3.577	−0.695	3.607	−0.581	0.411	0.873***	0.262	−0.122	0.138	−3.788***	0.454	−0.0597***	0.0135	0.309	0.389	0.00831	0.00597	−20.16***	5.262	2.522	3.572	1,105
(k)	JSP and CERTFOR	JSP	Property	−4.955**	2.379	−5.004**	2.362	−3.290	2.377	−3.167	2.390	1.802***	0.366	2.226***	0.234	0.119	0.0904	−4.101***	0.366	−0.0425***	0.0108	0.178	0.270	0.00744	0.00510	−6.609	4.466	5.587**	2.368	2,594
(l)	All policies	JSP	Property	−11.99***	4.440	−13.80***	4.437	−16.51***	4.702	−11.63***	4.476	3.574***	0.641	2.408***	0.631	0.559***	0.204	−2.963**	1.390	−0.158***	0.0446	1.484	1.048	−0.0423**	0.0169	−2.922	10.12	10.12**	4.757	550
(m)	CERTFOR	FSC	Property	27.33	26.29	32.07	26.35	21.30	26.49	31.02	26.38	1.649	1.980	0.686	1.740	0.209	0.382	6.701***	1.547	0.0456	0.0280	−1.018*	0.548	0.0699***	0.0142	30.10**	13.81	−34.20	26.07	372
(n)	JSP and FSC	FSC	Property	−1.512	2.659	−0.985	2.683	−2.240	2.694	−2.854	2.699	−2.310***	0.526	−1.047***	0.381	−0.00493	0.155	1.878***	0.525	−0.0233	0.0143	−1.407***	0.434	−0.00384	0.00710	22.60***	6.079	4.947*	2.712	964
(o)	JSP and CERTFOR	FSC	Property	−3.900**	1.935	−2.365	1.933	−4.375**	1.951	−3.498*	1.947	−0.185	0.473	0.145	0.364	0.0188	0.132	2.384***	0.455	−0.00521	0.0124	−1.248***	0.350	0.00606	0.00627	32.48***	5.383	5.668***	1.969	2,453
(p)	All policies	FSC	Property	−1.774	5.373	−1.124	5.433	−15.94***	5.766	−3.868	5.419	1.878**	0.869	−0.952	0.776	2.075***	0.524	12.54***	1.853	−0.117**	0.0564	−0.975*	0.582	−0.0862***	0.0230	20.19*	11.73	2.281	5.275	409
(q)	JSP and FSC	CERTFOR	Property	−39.00*	20.39	−43.62**	20.35	−37.56*	20.43	−43.73**	20.44	−5.985***	1.680	−3.211**	1.511	−0.0651	0.232	−2.186**	0.927	−0.0743***	0.0235	−0.494	0.613	−0.0803***	0.0120	21.67*	12.00	50.46**	20.37	756
(r)	JSP and CERTFOR	CERTFOR	Property	−39.42*	22.45	−42.16*	22.38	−38.44*	22.41	−42.20*	22.44	−2.147*	1.227	−0.497	1.112	0.193	0.220	−1.457*	0.765	−0.0437**	0.0210	−0.179	0.487	−0.0444***	0.00924	4.442	9.331	46.93**	22.19	2,245
(s)	JSP	CERTFOR	Property	−108.6**	43.08	−116.2***	43.33	−119.4***	44.69	−115.3***	43.75	−1.207	2.944	−3.993	2.781	0.890**	0.396	2.921	2.871	−0.0929	0.0590	3.947**	1.703	−0.209***	0.0484	−3.362	31.47	116.1***	42.22	201
(t)	JSP and CERTFOR	JSP and FSC	Property	−3.358***	1.274	−2.260*	1.266	−2.739**	1.280	−1.657	1.287	2.170***	0.334	1.243***	0.201	0.121	0.0955	0.0509	0.301	0.0160*	0.00941	−0.0873	0.221	0.00841*	0.00436	8.938**	3.593	2.062	1.302	2,837
(u)	All policies	JSP and FSC	Property	−8.485**	3.601	−10.07***	3.630	−15.98***	3.993	−9.524**	3.767	3.333***	0.623	0.263	0.594	1.337***	0.282	1.113	1.054	−0.127***	0.0432	0.840	0.829	−0.0815***	0.0173	21.51**	9.511	7.301*	3.924	793
(v)	All policies	JSP and CERTFOR	Property	0.449	1.805	−2.681	1.827	−6.641***	2.131	−2.430	1.895	1.797***	0.530	0.0429	0.510	0.443***	0.0984	3.326***	0.899	−0.107***	0.0364	0.948	0.600	−0.0805***	0.0142	5.605	7.444	−1.759	2.002	2,282
(w)	No policy, <4 km	No policy, >4 km	Property	0.553	3.302	1.654	3.293	1.747	3.403	1.353	3.397	0.597	1.137	1.337	1.031	−0.443**	0.215	0.00910	0.819	−0.131***	0.0301	3.220***	0.674	0.0429***	0.00910	35.63***	11.13	−7.450**	3.370	301
(x)	Any policy	No policy	Property	4.722*	2.541	5.366**	2.683	3.973	2.726	5.616**	2.714	−0.896	0.756	−0.886	0.685	−0.592**	0.274	−1.589	0.974	−0.00327	0.0271	3.761***	0.624	0.0404***	0.0120	1.974	11.38	−13.26***	2.796	4,060
			Company	4.231***	0.829	4.221***	1.410	−1.747	1.866	−5.440***	2.068	0.161	1.573	2.169**	0.950	1580.9***	307.4	2.977**	1.494	−0.176**	0.0690	−0.0477	0.0501	−0.0128	0.0123	25.60	20.87			

$***P < 0.01$; $**P < 0.05$; $*P < 0.1$.

Table S3. Normalized differences in property characteristics before and after balancing for each quasi-experiment

Label	Treatment	Control	Scale of covariate	Matched	Proportion agriculture in 1986	Proportion plantation in 1986	Proportion forest in 1986	Proportion shrub in 1986	Proportion moderate land quality	Proportion low land quality	Property size	Elevation	Slope	Distance to urban area	Plantation rents	Pre-treatment rate of forest conversion
(a)	JSP	No policy	Property	No	0.20	0.12	0.02	−0.52	−0.17	−0.23	−0.14	0.31	−0.06	−0.26	0.64	0.29
				Yes	−0.02	0.11	−0.12	0.02	0.00	−0.12	0.03	−0.07	0.01	0.07	−0.22	0.11
(b)	FSC	No policy	Property	No	0.27	−0.19	0.05	−0.21	−0.10	0.04	−0.23	−0.27	0.03	−0.35	0.73	−0.16
				Yes	0.05	0.10	−0.13	0.00	0.06	−0.01	−0.06	−0.07	−0.01	−0.05	−0.04	−0.02
(c)	CERTFOR	No policy	Property	No	−0.21	0.54	−0.25	−0.19	−0.07	0.14	−0.13	0.02	0.15	0.03	0.31	0.26
				Yes	−0.04	0.08	0.06	−0.14	−0.16	0.18	0.11	0.06	−0.04	0.08	−0.07	−0.13
(d)	JSP and FSC	No policy	Property	No	0.32	−0.03	−0.02	−0.39	−0.20	−0.13	−0.23	−0.03	−0.15	−0.31	0.63	0.10
				Yes	−0.01	0.08	−0.11	0.08	−0.08	−0.02	−0.13	0.03	0.06	0.17	−0.13	0.12
(e)	JSP and CERTFOR	No policy	Property	No	0.08	0.17	−0.05	−0.30	−0.15	0.10	−0.14	−0.09	0.00	−0.28	0.52	0.19
				Yes	−0.09	0.12	−0.12	0.11	−0.07	0.14	−0.05	−0.05	0.05	0.16	−0.05	0.07
(f)	All policies	No policy	Property	No	0.89	−0.19	−0.63	−0.46	0.47	−0.69	0.05	−0.20	−0.73	−0.72	0.56	0.19
				Yes	−0.17	0.16	0.15	0.00	−0.03	0.07	0.05	0.13	−0.08	−0.11	0.02	0.03
(g)	Any policy	No policy	Property	No	0.18	0.10	−0.05	−0.33	−0.13	−0.02	−0.14	−0.05	−0.05	−0.29	0.56	0.16
				Yes	−0.10	0.13	−0.10	0.12	−0.07	0.06	−0.06	−0.04	0.05	0.20	0.04	0.08
(h)	FSC	JSP	Property	No	0.05	−0.31	0.03	0.37	0.08	0.27	−0.08	−0.68	0.08	−0.12	0.26	−0.46
				Yes	−0.01	0.12	−0.08	−0.02	0.07	−0.09	0.04	−0.07	−0.14	−0.12	0.07	0.00
(i)	CERTFOR	JSP	Property	No	−0.41	0.40	−0.30	0.34	0.11	0.37	0.00	−0.35	0.20	0.37	−0.19	−0.04
				Yes	0.07	−0.03	−0.12	0.12	−0.13	0.11	0.02	0.08	−0.05	−0.06	0.01	−0.18
(j)	JSP and FSC	JSP	Property	No	0.10	−0.14	−0.05	0.15	−0.02	0.10	−0.09	−0.39	−0.09	−0.07	0.04	−0.20
				Yes	−0.04	0.03	0.03	−0.01	−0.05	0.06	0.01	−0.01	0.05	−0.03	0.04	0.03
(k)	JSP and CERTFOR	JSP	Property	No	−0.14	0.05	−0.07	0.24	0.03	0.33	0.01	−0.45	0.05	−0.03	−0.03	−0.11
				Yes	0.07	−0.06	0.03	−0.03	−0.01	0.00	−0.01	−0.03	0.05	−0.02	−0.02	0.03
(l)	All policies	JSP	Property	No	0.63	−0.30	−0.74	0.06	0.73	−0.36	0.11	−0.64	−0.60	−0.66	−0.14	−0.08
				Yes	0.01	0.00	0.09	−0.11	0.17	−0.10	−0.04	0.16	0.06	0.00	0.10	−0.08
(m)	CERTFOR	FSC	Property	No	−0.49	0.78	−0.32	0.01	0.04	0.09	0.08	0.36	0.12	0.49	−0.35	0.43
				Yes	−0.23	0.12	−0.04	0.21	−0.02	−0.02	0.04	−0.14	0.13	−0.18	−0.09	−0.04
(n)	JSP and FSC	FSC	Property	No	0.04	0.14	−0.08	−0.21	−0.11	−0.17	−0.01	0.28	−0.17	0.05	−0.21	0.26
				Yes	−0.05	0.07	−0.07	0.09	−0.09	−0.04	0.06	−0.02	−0.04	0.05	0.05	−0.08
(o)	JSP and CERTFOR	FSC	Property	No	−0.20	0.36	−0.10	−0.11	−0.05	0.06	0.09	0.21	−0.03	0.09	−0.24	0.36
				Yes	−0.03	0.15	−0.18	0.07	−0.01	−0.01	0.16	−0.13	−0.10	0.02	0.07	−0.01
(p)	All policies	FSC	Property	No	0.59	−0.03	−0.73	−0.30	0.65	−0.77	0.14	0.12	−0.69	−0.55	−0.36	0.35
				Yes	0.01	0.04	0.09	−0.10	−0.22	0.31	0.24	0.28	0.06	0.19	0.26	0.17
(q)	JSP and FSC	CERTFOR	Property	No	0.56	−0.54	0.26	−0.20	−0.14	−0.27	−0.08	−0.06	−0.29	−0.44	0.21	−0.16
				Yes	−0.08	0.08	0.04	−0.08	0.02	0.09	0.08	−0.13	0.22	−0.12	0.15	0.08
(r)	JSP and CERTFOR	CERTFOR	Property	No	0.32	−0.34	0.21	−0.11	−0.09	−0.04	0.00	−0.13	−0.15	−0.40	0.15	−0.07
				Yes	0.13	−0.10	−0.01	0.04	0.06	−0.08	−0.09	−0.13	0.11	0.02	0.13	0.11
(s)	All policies	CERTFOR	Property	No	1.18	−0.72	−0.50	−0.28	0.59	−0.94	0.11	−0.28	−0.80	−1.00	0.12	−0.05
				Yes	−0.48	0.56	−0.23	−0.20	−0.28	0.14	−0.07	−0.29	−0.10	−0.22	0.22	−0.08
(t)	JSP and CERTFOR	JSP and FSC	Property	No	−0.26	0.18	−0.03	0.10	0.05	0.23	0.09	−0.07	0.15	0.04	−0.06	0.10
				Yes	0.01	−0.02	0.01	0.03	0.00	−0.02	−0.02	0.04	0.00	0.07	−0.03	−0.02
(u)	All policies	JSP and FSC	Property	No	0.56	−0.16	−0.71	−0.08	0.77	−0.50	0.14	−0.20	−0.55	−0.60	−0.17	0.10
				Yes	0.09	−0.08	−0.04	−0.02	−0.02	−0.01	−0.05	0.06	−0.01	0.06	−0.03	0.06
(v)	All policies	JSP and CERTFOR	Property	No	0.85	−0.35	−0.63	−0.18	0.71	−0.86	0.11	−0.12	−0.71	−0.64	−0.07	0.02
				Yes	−0.03	0.05	−0.01	0.01	−0.06	0.00	0.03	−0.02	−0.03	−0.09	−0.04	0.07
(w)	No policy, <4 km	No policy, >4 km	Property	No	−0.14	0.05	0.08	0.03	−0.23	0.30	−0.10	0.03	−0.19	0.24	0.15	0.24
				Yes	0.00	0.06	−0.07	0.02	0.05	−0.05	−0.03	−0.02	−0.05	−0.17	0.12	0.03
(x)	Any policy	No policy	Property	No	0.18	0.10	−0.05	−0.33	−0.13	−0.02	−0.14	−0.05	−0.05	−0.29	0.56	0.16
				Yes	0.26	−0.25	−0.16	0.11	0.00	−0.31	0.04	0.33	−0.22	0.33	−0.48	0.16
			Company	No	0.97	1.32	1.19	0.56	0.95	1.19	0.98	1.42	1.10	0.69	−0.22	−0.03
				Yes	−0.43	−0.02	−0.15	−0.25	−0.36	−0.24	0.77	0.09	−0.07	0.04	−0.15	−0.09

Table S4. Difference-in-differences results

			Control								Treatment								Matched difference-in-differences							Matched difference-in-differences with spatial lag			
					1986–2001		2001–2011		Difference				1986–2001		2001–2011		Difference					Propensity score robust		Cluster robust				Cluster robust	
Label	Treatment	Control	*n*	*n* matched	Rate of forest conversion	Standard error	Rate of forest conversion	Standard error	Rate of forest conversion	Standard error	*n*	*n* matched	Rate of forest conversion	Standard error	Rate of forest conversion	Standard error	Rate of forest conversion	Standard error	Acceptable covariate balance	ATT	Percent change in forest conversion	Standard error	*P* value	Standard error	*P* value	ATT	Percent change in forest conversion	Standard error	*P* value
(a)	JSP	No policy	312	177	2.26	(0.17)	2.31	(0.17)	0.05	(0.15)	447	345	2.48	(0.07)	2.02	(0.07)	−0.45	(0.09)	True	−0.508	−20.1	(0.155)	0.0	(0.273)	0.07	−0.361	−15.2	(0.182)	0.05
(b)	FSC	No policy	312	182	1.82	(0.19)	2.06	(0.21)	0.24	(0.22)	293	248	1.78	(0.09)	1.15	(0.07)	−0.63	(0.08)	True	−0.87	−43.0	(0.19)	0.0	(0.318)	0.01	−0.581	−33.5	(0.191)	0.0
(c)	CERTFOR	No policy	312	167	2.49	(0.16)	2.7	(0.18)	0.2	(0.23)	83	51	2.24	(0.19)	2.04	(0.16)	−0.2	(0.23)	True	−0.397	−16.3	(0.254)	0.12	(0.23)	0.09	−0.007	−0.3	(0.31)	0.98
(d)	JSP and FSC	No policy	312	234	1.98	(0.14)	2.12	(0.15)	0.14	(0.16)	687	636	2.21	(0.05)	2.14	(0.06)	−0.07	(0.07)	True	−0.208	−8.9	(0.168)	0.22	(0.358)	0.56	−0.128	−5.6	(0.233)	0.58
(e)	JSP and CERTFOR	No policy	312	288	2.28	(0.11)	2.2	(0.14)	−0.08	(0.14)	2,223	2,129	2.41	(0.03)	2.21	(0.03)	−0.2	(0.03)	True	−0.125	−5.3	(0.164)	0.45	(0.257)	0.63	−0.181	−7.6	(0.18)	0.32
(f)	All policies	No policy	312	67	2.42	(0.31)	2.35	(0.43)	−0.07	(0.4)	130	68	2.48	(0.18)	2.21	(0.21)	−0.28	(0.2)	True	−0.204	−8.5	(0.405)	0.61	(0.487)	0.68	0.316	16.7	(0.351)	0.38
(g)	Any policy	No policy	312	281	2.19	(0.12)	2.27	(0.13)	0.08	(0.15)	3,863	3,724	2.35	(0.02)	2.09	(0.02)	−0.26	(0.03)	True	−0.338	−13.9	(0.15)	0.02	(0.245)	0.17	−0.28	−11.8	(0.171)	0.1
(h)	FSC	JSP	447	317	1.99	(0.17)	1.99	(0.16)	0.0	(0.18)	293	178	2.0	(0.1)	1.33	(0.09)	−0.66	(0.11)	True	−0.664	−33.2	(0.195)	0.0	(0.302)	0.05	−0.284	−17.5	(0.285)	0.34
(i)	CERTFOR	JSP	447	213	2.7	(0.16)	1.88	(0.14)	−0.81	(0.21)	83	56	2.38	(0.17)	2.04	(0.15)	−0.34	(0.2)	True	0.477	30.5	(0.261)	0.07	(0.058)	0.0	0.35	20.7	(0.125)	0.03
(j)	JSP and FSC	JSP	447	405	2.31	(0.1)	1.93	(0.1)	−0.38	(0.11)	687	596	2.36	(0.05)	2.26	(0.06)	−0.1	(0.07)	True	0.28	14.1	(0.138)	0.04	(0.297)	0.37	0.354	18.5	(0.207)	0.12
(k)	JSP and CERTFOR	JSP	447	425	2.39	(0.12)	1.94	(0.12)	−0.45	(0.13)	2,223	2,118	2.44	(0.03)	2.22	(0.03)	−0.22	(0.03)	True	0.225	11.3	(0.13)	0.08	(0.185)	0.25	0.265	13.6	(0.138)	0.08
(l)	All policies	JSP	447	120	2.55	(0.19)	2.22	(0.27)	−0.33	(0.27)	130	79	2.39	(0.16)	2.31	(0.17)	−0.07	(0.18)	True	0.259	12.6	(0.293)	0.38	(0.208)	0.27	0.466	25.2	(0.232)	0.1
(m)	CERTFOR	FSC	293	100	2.3	(0.25)	1.23	(0.16)	−1.07	(0.24)	83	37	2.22	(0.23)	2.11	(0.2)	−0.11	(0.25)	True	0.957	82.9	(0.345)	0.01	(0.186)	0.0	1.11	110.8	(0.243)	0.0
(n)	JSP and FSC	FSC	293	280	2.35	(0.14)	1.48	(0.1)	−0.87	(0.16)	687	635	2.19	(0.05)	2.12	(0.06)	−0.07	(0.07)	True	0.807	61.5	(0.143)	0.0	(0.418)	0.07	0.598	39.3	(0.368)	0.13
(o)	JSP and CERTFOR	FSC	293	284	2.45	(0.14)	1.53	(0.12)	−0.93	(0.18)	2,223	2,137	2.43	(0.03)	2.21	(0.03)	−0.22	(0.03)	True	0.709	47.2	(0.154)	0.0	(0.312)	0.04	0.372	20.2	(0.322)	0.26
(p)	All policies	FSC	293	62	1.89	(0.32)	1.5	(0.28)	−0.38	(0.43)	130	51	2.25	(0.21)	2.12	(0.25)	−0.13	(0.24)	False	0.251	13.5	(0.389)	0.52	(0.596)	0.69	0.098	4.8	(0.807)	0.91
(q)	JSP and FSC	CERTFOR	83	59	2.18	(0.35)	2.0	(0.37)	−0.17	(0.29)	687	337	2.35	(0.07)	2.13	(0.08)	−0.22	(0.09)	True	−0.045	−2.1	(0.249)	0.86	(0.262)	0.87	−0.234	−9.9	(0.277)	0.43
(r)	JSP and CERTFOR	CERTFOR	83	80	2.29	(0.21)	2.01	(0.19)	−0.28	(0.21)	2,223	1,704	2.49	(0.03)	2.18	(0.03)	−0.31	(0.04)	True	−0.037	−1.7	(0.213)	0.86	(0.119)	0.76	−0.151	−6.5	(0.11)	0.2
(s)	All policies	CERTFOR	83	17	2.15	(0.48)	2.14	(0.52)	−0.01	(0.62)	130	8	2.02	(0.23)	2.07	(0.33)	0.04	(0.33)	False	0.05	2.5	(0.496)	0.92	(1.094)	0.97	0.713	52.7	(1.2)	0.61
(t)	JSP and CERTFOR	JSP and FSC	687	659	2.46	(0.06)	2.15	(0.06)	−0.31	(0.07)	2,223	2,142	2.43	(0.03)	2.2	(0.03)	−0.22	(0.03)	True	0.089	4.2	(0.078)	0.25	(0.256)	0.73	0.043	2.0	(0.173)	0.81
(u)	All policies	JSP and FSC	687	187	2.14	(0.19)	2.3	(0.2)	0.16	(0.28)	130	81	2.25	(0.16)	2.24	(0.16)	−0.01	(0.18)	True	−0.173	−7.2	(0.265)	0.51	(0.449)	0.72	−0.434	−16.2	(0.446)	0.38
(v)	All policies	JSP and CERTFOR	2,223	431	2.28	(0.14)	2.39	(0.16)	0.11	(0.15)	130	104	2.43	(0.14)	2.28	(0.16)	−0.15	(0.17)	True	−0.256	−10.1	(0.185)	0.16	(0.232)	0.3	−0.711	−23.8	(0.278)	0.03
(w)	No policy, <4 km	No policy, >4 km	186	102	2.17	(0.21)	2.59	(0.19)	0.42	(0.19)	126	90	2.23	(0.13)	2.24	(0.15)	0.01	(0.18)	True	−0.412	−15.6	(0.255)	0.11	(0.345)	0.24	−0.336	−13.1	(0.273)	0.22
(x)	Any policy	No policy	312	131	2.13	(0.44)	2.41	(0.26)	0.27	(0.38)	3,863	177	2.46	(0.11)	1.67	(0.09)	−0.8	(0.12)	False	−1.069	−39.1	(0.309)	0.0	(0.227)	0.0	−0.793	−32.2	(0.195)	0.0