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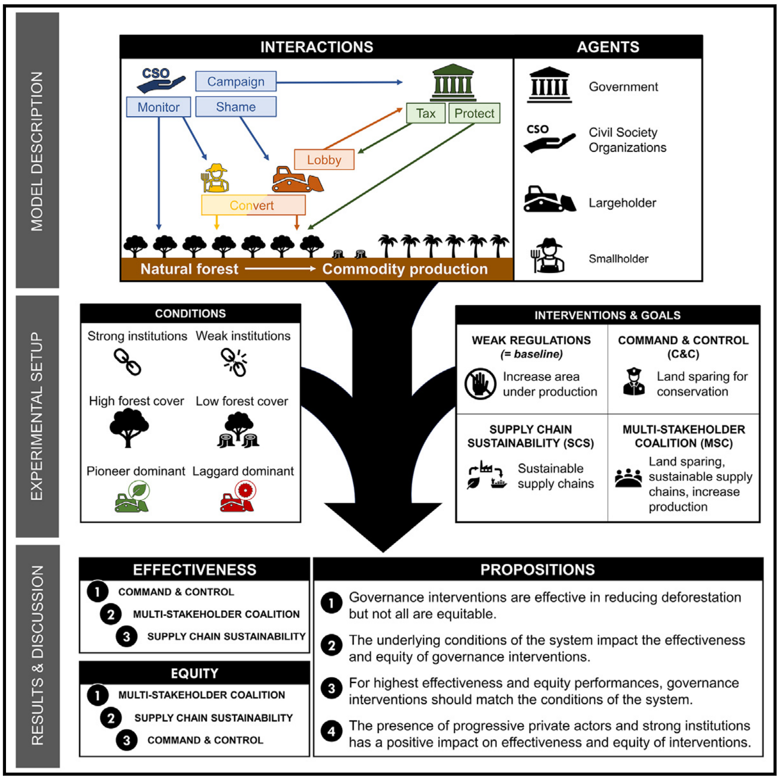
Modeling conditions for effective and equitable land use governance in tropical forest frontiers

Graphical abstract



Highlights

- Interventions reduce deforestation, but effectiveness varies, and not all are equitable
- Multi-stakeholder approaches provide the best trade-off between effectiveness and equity
- Intervention performance is impacted by underlying environmental and social conditions
- Strong institutions and progressive private actors have positive impact on performance

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In brief

The proliferation of governance interventions to address forest conversion in the tropics over the past two decades does not yet correlate with significant reductions in deforestation at the global scale. The effectiveness and equity of interventions to reduce deforestation vary substantially and are significantly impacted by the environmental and social conditions of the landscape in which they are embedded. Policymakers need to consider these conditions and be aware of effectiveness-equity trade-offs when designing governance interventions.

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Modeling conditions for effective and equitable land use governance in tropical forest frontiers

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SCIENCE FOR SOCIETY Despite two decades of governance efforts, tropical deforestation and degradation due to unsustainable resource use remain problems. It is vital to identify governance interventions that balance environmental protection and social well-being and better understand under which conditions interventions perform best.

Simulating three governance interventions shows that each can reduce deforestation, but not all are equitable. Performance of these interventions varies substantially with changes in environmental and social conditions of the landscape. On average, collaborative approaches between local or regional governments, civil society, and the private sector provide the best balance between effectiveness and equity. The presence of strong institutions and progressive private actors has the biggest impact on intervention success. Policymakers need to consider the underlying conditions alongside trade-offs between effectiveness and equity when designing interventions.

SUMMARY

Deforestation and degradation driven by unsustainable agricultural expansion remain pressing global challenges. Over the past two decades, a variety of governance efforts to reduce deforestation and degradation in the tropics have emerged. Assessing if and under which conditions interventions are effective and equitable, however, is challenging given their long implementation times and methodological limitations. Here, we use an agent-based model to assess effectiveness, equity, and transaction costs of four archetypal governance interventions (weak regulation to natural resource access, command and control, supply chain sustainability, and multi-stakeholder coalitions) under different environmental and social conditions. We find that all interventions are effective in reducing deforestation, albeit to varying degrees, and not all are equitable. Intervention performance varies significantly across conditions, and on average, multi-stakeholder coalitions provide the best balance between effectiveness and equity. Policymakers therefore need to consider the local context and potential effectiveness-equity trade-offs when designing interventions to reduce deforestation and degradation.

INTRODUCTION

Deforestation caused by the production and extraction of natural resources is a major threat to tropical ecosystems.[1,2] Despite a proliferation of interventions to reduce deforestation since the 1950s, forest loss and degradation are still ongoing.[3,4] Early public policy interventions that focused on disincentivizing deforestation (e.g., through land use zoning) and incentivizing environmentally friendly behavior (e.g., through subsidies or payments for ecosystem services) were complemented by initiatives from civil society organizations (CSOs) encouraging forest-friendly practices (e.g., initiatives to promote sustainable production and trade of agricultural commodities) and eventually by private sector actors seeking to remove deforestation from commodity supply chains (e.g., zero-deforestation commitments).[5–7] More recently, we see an increase in interventions composed of actors from multiple stakeholder groups in the form of public-private partnerships and landscape and jurisdictional approaches.[8–11]

Today, governance interventions to reduce tropical deforestation cover over a third of tropical forests globally and vary in geography, stakeholder composition, and governance strategy.[12,13] While many interventions conceptually have the potential for success,[14,15] achieving effective and equitable outcomes remains challenging,[16] and the proliferation of initiatives on the ground does not yet correspond to a significant reduction in deforestation at the global scale.[17] This mismatch invites the questions whether certain approaches perform better than others and, if so, why.

Assessing governance interventions in tropical forest frontiers is challenging as they are typically implemented over long periods of time into complex socio-ecological systems, making it difficult to control for confounding factors and assess the full life cycle of an intervention. The conditions into which these interventions are implemented are also prone to change over time, as in Brazil where a change in government had an impact on regulatory enforcement. Additionally, there are methodological barriers. For example, the use of true experiments is ethically or politically questionable when the random assignment to treatment or control group has implications for the well-being of participants.[18,19] Observational studies such as natural experiments are criticized for their reliance on "as if random" assignment of participants to treatment and control groups and are further limited by the inability of the researchers to manipulate the treatment and the social and environmental conditions of the study system.[20,21] Study designs that rely on small sample sizes, including case studies, enable in-depth assessment of specific cases but do not generate generalizable insights.[22] Studies with large sample sizes that use statistical inference to establish cause-and-effect relationships are critiqued for being broad yet shallow and thereby at risk of dismissing important conditions such as law enforcement or land tenure arrangements.[23,24] Additionally, obtaining a large enough sample with sufficient data quality may be challenging in the case of land use governance interventions in the tropics. These challenges have led to research gaps regarding the effectiveness and equity of interventions to reduce tropical deforestation. Prior studies have predominantly relied on case studies. A diversification of methodological approaches may help to establish a more comprehensive and systematic understanding of how governance interventions perform.

Software modeling offers such a complementary approach by testing theories and mechanism under varying social and environmental conditions in a virtual environment that allows for iteration, manipulation, and random assignment of treatments.[25] Using an agent-based model, we simulate governance interventions to reducing deforestation in tropical commodity frontier systems. Agent-based simulation is a bottom-up modeling approach where individual agents interact with each other and their environment according to a set of user-defined rules.[26] Collectively, these micro-interactions have an impact on the agents and their environment that can be observed and analyzed at the system scale.[27] Agent-based modeling is employed in a variety of scientific contexts and is frequently used to simulate socio-ecological systems, land use change, and environmental policy.[28,29]

The objective of this study is to better understand the relationships between governance interventions, core stakeholder groups, and some key conditions of the systems, with a focus on large-holder commodity producers and their responses to interventions and changes in key conditions. We define conditions as elements that characterize the environment into which interventions are implemented, such as land cover composition, institutional capacity of public and civil society actors, and composition of private actors. Such underlying conditions change with geography, culture, time, and history and may impact the effectiveness and equity of an intervention. Here, we aim to answer the following research questions: how do governance interventions to reducing deforestation perform under varying conditions? Which conditions are most conducive to the effectiveness and equity of governance interventions? How do interventions perform with respect to the potential trade-offs between achieving effectiveness and equity and the associated number of transactions? Which intervention performs best in key commodity-producing systems in the tropics, such as palm oil in Indonesia and soy in the Brazilian Amazon? We use a two-tiered study design. First, we vary one condition at a time to create experiments that isolate the impact of each condition on the effectiveness and equity of the interventions. Next, we create scenarios by simulating multiple conditions simultaneously to test their combined impact on the effectiveness and equity of the interventions.

Model description

We utilize the Agent-Based Simulation of Land Use Governance (ABSOLUG) to simulate land use governance interventions (Table 1) under varying social and environmental conditions (Table 2).[30] ABSOLUG simulates the interactions between small- and large-holder commodity producers, CSOs, and government entities within a generic tropical commodity-producing landscape (Figure 5). Small- and large-holder agents (henceforth producers) strive to maximize their profits from cultivating crops by moving across the landscape, converting forest to cropland, and intensifying or eco-certifying existing cropland. Small-holder producers represent households that practice shifting cultivation and commodity crop production (see detailed model description).[31] Large-holder producers are further categorized into pioneers, mainstreamers, and laggards based on the degree to which they value reputation and how inclined they are toward employing sustainable production practices (i.e., eco-certification and intensification).

Here we simulate four intervention archetypes (weak regulation to natural resource access, command and control, supply chain sustainability, and multi-stakeholder coalitions) under varying environmental and social conditions to assess their effectiveness in reducing deforestation, social equity, and transaction costs. We further test the interventions in two scenarios resembling existing commodity systems: soy in the Brazilian Amazon and palm oil in Indonesia. We find that while all interventions are effective in reducing deforestation, not all are equitable, and effectiveness varies substantially across experiments. The social and environmental conditions of the system have significant influence on the performance of the intervention, and the scenarios demonstrate that changes in the conditions affect the effectiveness and equity of the interventions. The presence of strong institutions and progressive private actors strongly correlates with effectiveness and equity of the interventions, and on average, multi-stakeholder coalitions provide the best balance between environmental protection and social well-being. When designing governance interventions, policymakers need to carefully prioritize their objectives as not all outcomes can be maximized simultaneously. Further, the environmental and social context significantly influences the performance of interventions and needs to be accounted for in the intervention design.

Research design

We use ABSOLUG to explore the impact of key social and environmental conditions on the performance of governance interventions with respect to effectiveness and equity.[32] Conditions are typically outside the purview of policymakers and are of environmental (e.g., land cover composition), institutional (e.g., integrity and capacity of the government), regulatory (e.g., illegality of forest conversion), or societal nature (e.g., stakeholder composition).[10,33] Interventions represent governance and policy archetypes whose design and implementation are within the purview of key stakeholder groups like governments (e.g., command and control approaches to land use zoning), private actors (e.g., deforestation-free supply chains), or multi-stakeholder coalitions (e.g., jurisdictional approaches to sustainable resource use).

We identified four interventions—weak regulations, command and control, supply chain sustainability, and multi-stakeholder coalition—and three categories of conditions—institutional capacity, land cover composition, and stakeholder composition, which we simulate in two steps. First, we modify one condition at a time and simulate each intervention under the resulting combinations of conditions, leading to twenty-six unique experiments. We analyze the results 2-fold: "by intervention," to isolate the effectiveness and equity of each intervention, and "by condition," to isolate the impact of each condition on the performance of the interventions. Second, we generate scenarios to analyze the performance of each intervention under combinations of conditions that mimic real-world systems, which experience changing conditions over time (e.g., through elections or changes in commodity prices). The scenarios resemble a soy production system in the Brazilian Amazon and a palm oil production system in Indonesia as these two crops are major causes of commodity-driven deforestation. To represent these systems, we adjust the three sets of conditions to match empirically observed characteristics: strength of civil and public institutions (institutional capacity), extent of forest cover (land cover composition), and composition of categories of large-holder producers (stakeholder composition). Changes in the conditions over time are replicated through two rounds of simulations, where in the second round the conditions change from a strong, pro-environmental government to one that prioritizes forest frontier expansions in the soy scenario, and a shift from mostly regressive to mostly progressive large-holder producers in the palm oil scenario (see experimental procedures for further details). We simulate all interventions (weak regulations, command and control, supply chain sustainability, and multi-stakeholder coalition) in each round.

We assess intervention performance using indicators for effectiveness and equity. For effectiveness, we measure forest extent of the interventions compared to *baseline*. For equity, we monitor land dispossessions as the illegal appropriation of smallholder-owned land by largeholders (land grabbing) and the expropriation of private property by the government for the purpose of protected area designation (expropriation). First, we average performance of each intervention across the twenty-six experiments to assess to what degree the interventions achieve effectiveness and equity across varying conditions. Second, we average the effectiveness and equity of the interventions for each condition to isolate the impact of the conditions on the performance of the interventions. Additionally, we capture the area placed under formal protection by the government to discriminate between differences in forest extent due to changes in production processes (e.g., increase in eco-certified production) and land use zoning (i.e., declaration of protected areas). As a proxy for transaction costs of each intervention, we monitor the volume of transactions between stakeholders. Transactions are defined as interactions between actors pertaining to the operation of the interventions. We measure changes in transactions relative to the baseline experiment. Specifically, we monitor occurrences of large-holder producers lobbying the government, CSOs campaigning the government (summarized as lobbying and campaigning), CSOs shaming largeholders for encroaching protected areas, and the government fining largeholders for encroaching protected areas (summarized as fining and shaming). The simulation period is forty years, which we hold sufficient for socio-ecological processes to take place, and the implementation period for interventions is twenty years, which is a frequently observed life cycle in large-scale governance interventions.[34,35] The conditions, interventions, and scenarios are described in full detail in the experimental procedures.

RESULTS

Intervention performance across conditions

When analyzing the experiment results by intervention, we find that the baseline experiment (*weak regulations* intervention under *baseline* conditions) results in 89% forest loss (from 14,628 to 1,509 parcels) of which 25% is caused by smallholders and 75% by large-holder producers. All three interventions conserve significantly more forest than baseline (Figure 1) with command and control being the most effective with a forest extent of 4,186 parcels, protecting a significantly larger area than supply chain sustainability (2,302 parcels) and multi-stakeholder coalition (3,073 parcels). Specific experiments show that interventions can lead to substantial reductions in deforestation; e.g., the command-and-control intervention under pioneer dominant conditions preserves almost three times (4,557 ha) as much forest compared to no intervention (1,613 ha). Other experiments, such as supply chain sustainability in a laggard dominant system, generate substantially fewer conservation gains (1,784 ha and 1,444 ha respectively).

All interventions see significantly lower levels of land grabbing compared to baseline, with the fewest parcels grabbed under multi-stakeholder coalition (503 parcels), while command and

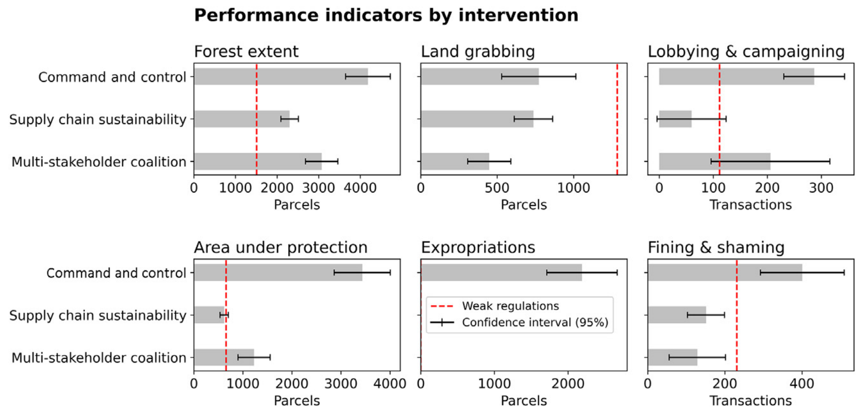

Figure 1. Performance indicators for three interventions

The values for the performance indicators are averaged across all conditions. The error bars represent a 95% confidence interval around the mean, and the dotted vertical line represents results for weak regulations under baseline conditions.

control and supply chain sustainability perform similarly (854 and 819 parcels respectively). Command and control is the only intervention that leads to land expropriations (2,073 parcels) and a significantly higher volume of transactions (280 lobbying and campaigning and 416 fining and shaming transactions).

Impact of conditions on intervention performance

The strong institutions condition contributes the most to effectiveness with a forest extent of 3,528 parcels, followed by pioneer dominant (3,218 parcels) and high forest cover (3,180 parcels). Weak institutions result in the least effective intervention performances with a forest extent of 2,250 parcels (Figure 2). Area under protection is significantly higher than baseline under strong institutions and significantly lower under weak institutions.

Regarding equity, pioneer dominant and high forest cover see significantly less land grabbing than baseline (652 and 595 parcels respectively), while the averages for weak institutions and laggard dominant are slightly above baseline. For the second equity indicator expropriation, only weak institutions perform significantly below baseline. The transaction indicators show large confidence intervals, and only strong institutions have significantly more lobbying and campaigning transactions than baseline. The laggard dominant condition results in significantly more fining and shaming transactions compared to baseline.

Effectiveness-equity trade-offs

Performance across experiments varies widely, with interventions accounting for most of the variability in effectiveness and equity compared to conditions across all experiments (see clusters in Figure 3). Command and control under strong institutions avoids the most deforestation while incurring the second highest land dispossessions and very high levels of transactions (Figure 3). Multi-stakeholder coalition under pioneer dominant achieves low levels of deforestation, land dispossessions, and transactions. All experiments that are composed of an active intervention are effective; i.e., they show lower levels of deforestation than baseline. With respect to equity, all supply chain sustainability and multi-stakeholder coalition experiments display

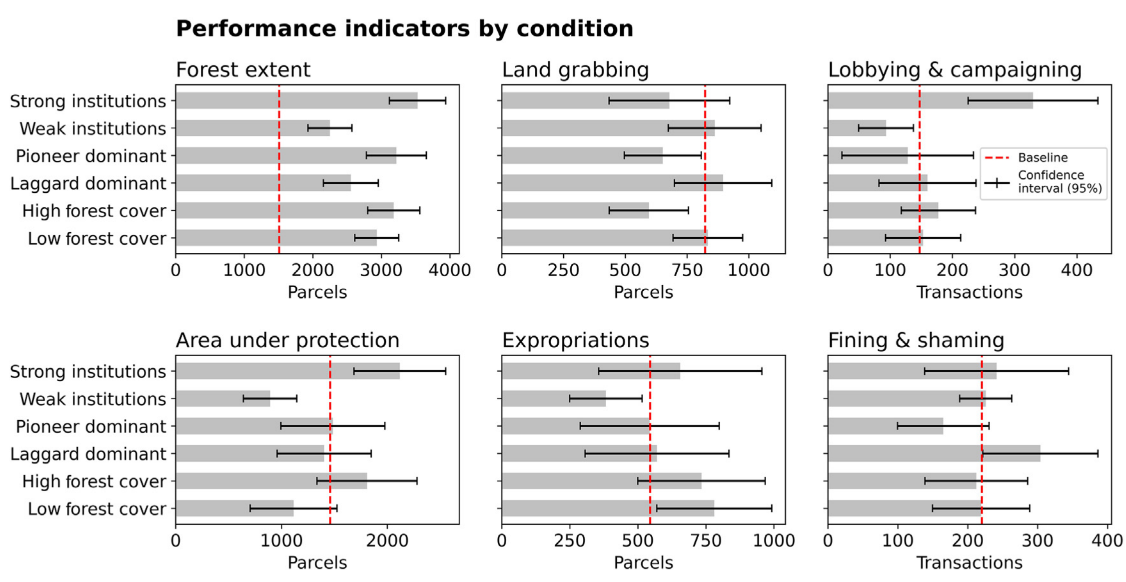

Figure 2. Performance indicators for six conditions

The values for the performance indicators are averaged across all interventions. The error bars represent a 95% confidence interval around the mean, and the dotted vertical line represents results for weak regulations under baseline conditions.

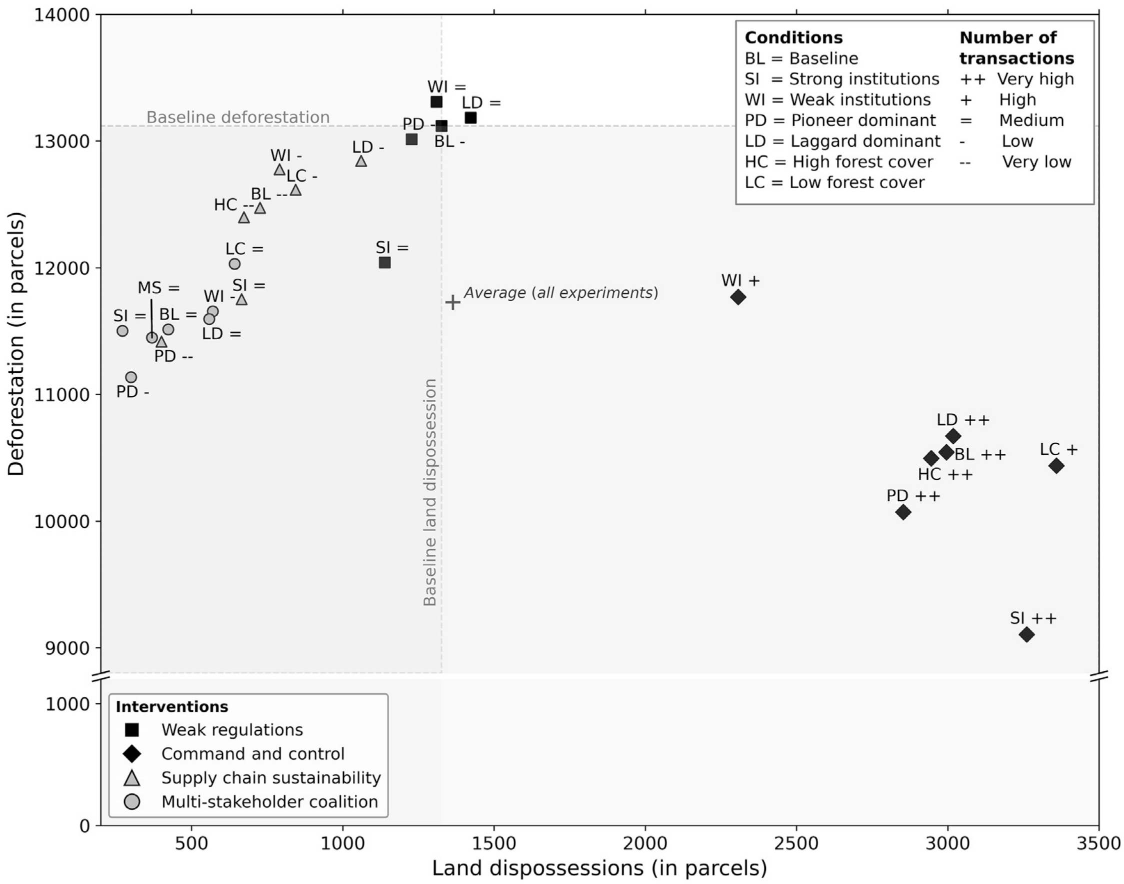

Figure 3. Effectiveness (in parcels of deforestation) and equity (in parcels of dispossessed land) and transactions of experiments

Very high transactions are values above one standard deviation above the mean, high values are between a half and one standard deviation above the mean, medium values are between a half standard deviation below and above the mean, low values are between a half and one standard deviation below the mean, and very low values are below one standard deviation below the mean. The shaded areas depict deforestation (horizontal) and land dispossessions (vertical) below baseline.

fewer land dispossessions than baseline, while all command and control experiments show significantly higher levels.

Experiments that feature the pioneer dominant condition perform most equitably within their respective intervention, and experiments under strong institutions display lower than average levels of deforestation. Experiments with the multi-stakeholder coalition intervention have the most balanced performance with respect to effectiveness and equity, clustering around low levels of land dispossessions and deforestation. Their transaction numbers, however, are on average higher than those of supply chain sustainability experiments. Command and control experiments show the highest levels of transactions.

Intervention performance in the soy and palm oil scenarios

In both scenarios, interventions are more effective than baseline (weak regulations). Additionally, the multi-stakeholder coalition and supply chain sustainability interventions are also more equitable than baseline (Figure 4). The command and control intervention is the most effective followed by multi-stakeholder coalition and supply chain sustainability. Command and control also incurs the most land dispossessions in both scenarios and incurs the most transactions. Supply chain sustainability performs similar to baseline with respect to effectiveness and equity and shows the least number of transactions in both scenarios (low).

In the soy system, the discrepancy in effectiveness and equity between the command and control and the remaining two interventions is substantial: the former avoids over 40% more deforestation than the latter two while incurring almost seventeen times as many land dispossessions as supply chain sustainability. For the palm oil system, the trend is similar, albeit not as pronounced. Here, effectiveness of the multi-stakeholder coalition is closer to that of command and control with 26% and 20% of original forest cover retained respectively. The difference in effectiveness between supply chain sustainability and multi-stakeholder coalition is more pronounced compared to the soy system.

Changes in the conditions of the system have noticeable impact on the performance of interventions. The upward-facing arrow in the soy system indicates that, on average across the interventions, deforestation increases. The downward and left-facing arrow in the palm oil system indicates less deforestation and fewer land dispossessions compared to previous conditions. In the soy system, the shift from high to low institutional capacity results in an increase in deforestation of 13% and land

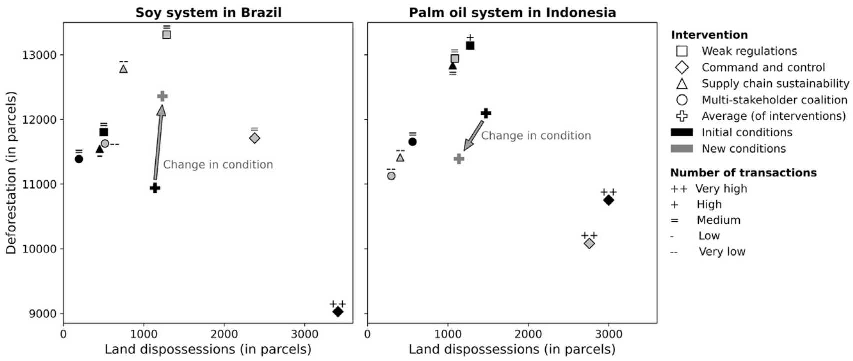

Figure 4. Effectiveness (in parcels of deforestation) and equity (in parcels of dispossessed land) and transactions of governance interventions in the soy and palm oil scenarios

In the soy system, conditions change from strong to weak institutions, representing a change in government. In the palm oil system, conditions change from regressive to progressive large-holder producers, representing widespread adoption of zero-deforestation commitments. An upward-facing arrow indicates higher deforestation and a downward-facing arrow lower deforestation. Very high transactions are values above one standard deviation above the mean, high values are between a half and one standard deviation above the mean, medium values are between a half standard deviation below and above the mean, low values are between a half and one standard deviation below the mean, and very low values are below one standard deviation below the mean.

dispossessions of 8% (Figure 4). While all interventions perform differently under the new condition, the differences are particularly pronounced in the government-led command-and-control intervention, which is 30% less effective and 30% more equitable. In the palm oil system, the shift toward more progressive largeholders leads on average to improved effectiveness (6% less deforestation) and equity (23% fewer land dispossessions), with supply chain sustainability displaying the largest improvement (11% less deforestation, 61% fewer land dispossessions).

DISCUSSION

Using the ABSOLUG model enabled us to overcome some of the limitations associated with more traditional policy evaluation methods by, for example, testing the performance of interventions against counterfactuals[19] and thereby providing a complementary method to evaluate governance approaches to reduce tropical deforestation. We were able to simulate interventions in a variety of settings, providing further evidence that effectiveness and equity are—among other factors—contingent on the interaction between interventions and conditions. We discuss the results in four propositions.

Proposition 1: Governance interventions are effective in reducing deforestation, but not all are equitable

Our results show that the three governance interventions command and control, supply chain sustainability, and multi-stakeholder coalition, are effective in reducing deforestation in tropical forest frontiers, but not all result in reduced inequity when compared to a business-as-usual scenario. While deforestation reduction is statistically significant across all interventions, certain experiments lead to only marginally better conservation outcomes compared to a no-intervention baseline. Deforestation reduction frequently coincides with increases in land dispossessions and higher production costs, resulting in more lobbying and campaigning transactions. Interventions need to strike a balance between ambitious environmental outcomes and maintaining the support of CSOs and the profitability of producers.

On average, command-and-control approaches that rely on the designation and enforcement of protected areas are most effective and least equitable. Our findings corroborate that protected areas have great potential in reducing deforestation when managed more strictly,[36] while high levels of land dispossession and transactions suggest equity concerns and operational inefficiencies respectively.[37] Such inequity can endanger the performance of interventions when stakeholders cease to collaborate or turn into opponents.[38] Transaction costs can account for a third of the total costs of an intervention, especially when addressing complex socio-ecological problems like tropical deforestation.[39,40] Our results point to the challenge of achieving the triple bottom line of maximizing effectiveness and equity while minimizing the cost of the intervention.[16,39]

We find that supply chain sustainability is the least effective intervention, confirming observations that private sector commitments have so far failed to reduce deforestation globally.[17] The exception is when the intervention is implemented into a stakeholder environment dominated by progressive actors, matching real-world cases like the Amazon Soy Moratorium whose success was contingent on institutional support and a coalition of private actors responsible for 90% of the soy trade in the Amazon.[41]

According to our findings, multi-stakeholder coalitions can effectively reduce deforestation while performing more equitably than other interventions. Conceptually, multi-stakeholder initiatives like jurisdictional approaches or public-private partnerships are considered fit to achieve the twin goals of effectiveness and equity[12] but have yet to be comprehensively tested in practice. In the absence of empirical evaluations, our results provide a first indication that multi-stakeholder coalitions are well equipped to reduce deforestation without sacrificing equity. Considering the increasing recognition that successful interventions need to achieve both effectiveness and equity,[38] policymakers should consider multi-stakeholder coalitions when determining governance interventions.

Proposition 2: The underlying conditions of the system impact the effectiveness and equity of governance interventions

We find that the interventions—designed to promote sustainable commodity production—account for most of the variability in our results. When examining the experiments within each intervention more closely, our findings reinforce the hypothesis that key conditions like institutional capacity, stakeholder composition, and remaining forest cover have significant influence on the success of interventions.[33,42,43] The absence of strong political and civil society institutions, for example, reduces the effectiveness of all interventions, while a private sector dominated by pioneers leads to less deforestation and land grabbing. This is consistent with observations that political and institutional capacity is a prerequisite for policy innovation and diffusion[44] and that the presence of pioneer actors facilitates the emergence of progressive approaches to sustainability.[14,45]

The significance of conditions is further emphasized by cases where conditions changed over time. We find that a shift from strong, pro-environmental institutions to weak, pro-expansion institutions in the Brazilian soy scenario results on average in more deforestation. This mirrors the trajectory observed in Brazil where deforestation rates increased after President Jair Bolsonaro took office in 2019.[46] In our palm oil scenario, a change among largeholders to adopting more environmentally friendly practices led to improvements in effectiveness and equity across all interventions and in particular for the supply chain intervention. This aligns with observations from the Indonesian palm oil sector where exports under zero-deforestation commitments rose from 0% in 2013 to over 85% in 2022 and are now associated with lower deforestation risk.[47]

Proposition 3: For highest effectiveness and equity performances, governance interventions should match the conditions of the system

Interventions are most effective and equitable when they are adapted to the environmental conditions in which they are implemented, emphasizing the risk of relying on one-size-fits-all approaches.[48] For example, supply chain interventions in combination with a pro-environment private sector outperform all other supply chain experiments. Pioneer producers are open to eco-friendly production and reluctant to engage in reputation-harming activities, so when combined with a supply chain-focused intervention these characteristics can reduce deforestation while maintaining moderate equity performance and minimal friction.

This tendency is corroborated in our scenarios, where the government-led command-and-control intervention is most effective in both the soy and palm oil systems but at the expense of equity and high transaction counts. Strong institutional capacity and high forest cover in the soy scenario support a reduction in deforestation. In the palm oil system, the multi-stakeholder coalition can raise the floor for all large-holder producers with regard to production sustainability while receiving support from the government and CSOs, resulting in moderate deforestation reduction alongside reduced transactions and high equity scores.

While matching interventions to the underlying conditions positively impacts performance, a mismatch can do so negatively. In our simulations, supply chain interventions perform poorly when most actors are opposed to eco-certification and focus instead on expanding their area under cultivation. Examples of a poor fit between intervention and conditions are the Brazilian Cattle Agreements and the "G4" agreement. In 2009 the largest meatpacking companies operating in Brazil committed to blocking sales from properties that were cleared after 2009 or not registered in Brazil's Rural Environmental Registry.[49] Modeled after the Amazon Soy Moratorium, these agreements failed to capture the complexity of the beef supply chain and did not apply to upstream actors who continued to use recently deforested land for calving or rearing operations, limiting the scope and impact of the agreements.[17,50]

Proposition 4: The presence of progressive private actors and strong institutions has a positive impact on the effectiveness and equity of governance interventions

Strong civic and government institutions significantly reduce deforestation, and two out of four interventions are most effective in such environments. In Costa Rica, for example, the combination of strong public institutions, direct state interventions, and policies that incentivize sustainable behavior have led to a forest transition,[51] and in the Brazilian state of Mato Grosso, the government initiated the promising Produzir, Conservar, Incluir initiative.[52] A private sector dominated by progressive private actors is the second strongest facilitator for avoiding deforestation. All interventions were more effective and equitable in the presence of pioneer actors, and supply chain and multi-stakeholder interventions performed best under this condition. Private actors who control a large share of a commodity market and are willing to engage in pro-environmental governance interventions are the foundations for the success of initiatives like the abovementioned Amazon Soy Moratorium. However, the Soy Moratorium appears to be an exception as private actors overall are struggling to comply with commitments to remove deforestation from their supply chains.[17,53]

Our results highlight the importance of governments in reducing deforestation. Government-led command-and-control interventions are the most effective interventions, and the presence of strong political institutions is positively correlated with effectiveness across interventions. This supports the notion that governments can influence forest conversion 2-fold: directly by implementing and enforcing policies to protect natural resources and indirectly by creating a regulatory environment that is conducive to private and civil action.[14]

Theoretical implications

Our results confirm the importance of inclusive governance approaches that give a voice to all stakeholders—local government, local communities, CSOs, private actors—and that combine multiple interventions in a coordinated policy mix that is adapted to the specific conditions of the jurisdiction.[38,54] Equitable outcomes can best be achieved through multi-stakeholder governance interventions with strong institutions and an orchestration by governments to ensure that all dimensions of sustainability are pursued, and the weakest actors are not further marginalized.[55] Our findings also confirm that an overreliance on law enforcement to combat deforestation can lead to negative impacts on equity, particularly for marginalized producers.[38] Further, underlying social and environmental conditions have a significant influence on the effectiveness and equity of governance interventions, in a way that needs to be made more explicit when designing interventions.

Conclusions

The last decade has seen a proliferation of treaties and pledges to halt deforestation and transform supply chains.[56–58] Governance and policy interventions, particularly at the jurisdictional level, are considered an integral part of achieving these goals. However, interventions are embedded in a complex network of social, ecological, political, and cultural conditions, which has prevented comprehensive assessments. Our simulation modeling approach starts to address the resulting research gap. According to our findings, multi-stakeholder coalitions like jurisdictional approaches provide the best trade-off between effectiveness and equity across a range of conditions. On average, all interventions are effective, but some perform only marginally better than baseline, while others lead to substantial forest conservation gains. We also find that the effectiveness and equity of all interventions vary substantially with changes in the social and environmental conditions of the system. Strong institutions and the presence of progressive large-holder producers show the highest correlation with effectiveness and equity. Moreover, interventions are most successful when they match the underlying conditions. In conclusion, all governance approaches are effective, albeit to varying degrees, and policymakers need to consider equity, transaction costs, and the underlying social and environmental conditions when assessing policy options.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Marius von Essen (vonessen@alumni.stanford.edu).

Materials availability

This study did not generate new unique materials.

Data and code availability

The python code for the figures is deposited under https://github.com/mvonessen/vonEssenLambin_OneEarth. The full model description and code is deposited in the CoMSES computational model library under https://www.comses.net/codebases/ead4f596-6987-4829-9c33-08144bda3a03/releases/1.1.0/. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

Method

Detailed model description

Our study utilizes the ABSOLUG model, which is designed to examine the interactions between governments, large-holder commodity producers, smallholders, and civil society actors and the impacts of different land use governance approaches on deforestation.[30] ABSOLUG simulates a generic tropical commodity-producing landscape featuring homogeneous forest, a central marketplace, and two rivers. The landscape is represented as a grid of cells across which agents move and interact in discrete time steps. Conceptually, ABSOLUG incorporates several land use theories and frameworks. In the theory of socio-ecological systems, social and ecological features interact and influence natural resource regulations that are enacted by a diverse set of institutions, including governments, civil society, private actors, and cultural norms, which forms the foundation of the model.[59,60] The forest-transition framework posits that forest cover changes over time, and land use is measured in steps along the forest transition curve, from high forest cover frontiers to landscapes dominated by agricultural and forest mosaics.[61] According to the governance triangle framework, private (producers), public (government), and civil society actors interact and shape the regulatory standard setting process,[62] which is represented in the model by the ability of large-holder producers and CSOs to influence government regulatory processes through lobbying and campaigning. Large-holder producers move through the model landscape, creating resource frontiers when land is abundant and capital is scarce, engaging in a race for resource accumulation.[63,64] In later stages of the simulation, frontier expansion is mostly driven by large-holder producers because of their superior capability to appropriate land rents.[64] Thus, the deforestation frontier is developed in accordance with the theories of neoliberal and commodity frontiers, where expansion is motivated by demand for commodities, rather than state planning or government subsidies to motivate migration.[65,66] As land becomes scarcer throughout the simulation, agents increase the profitability of their land through intensification or certification.[67] The theory of induced intensification is represented in model scenarios where the government implements institutional constraints on land access, e.g., fines on deforestation or establishment of protected area, thus inducing intensification and certification.[68]

A central mechanism of the model is the production of agricultural commodities by smallholders and large-holder producers. Large-holder producers utilize parcels of land to generate economic rent, following von Thünen's land rent theory of increasing rents with proximity to the central marketplace,[69] and large-holder producers strive to maximize their profits from cultivating crops and move across the landscape, converting forest to cropland and intensifying or eco-certifying existing cropland—dynamics that still have validity in commodity production systems today like palm oil (distance to mills) or soy and beef (frontier expansion through cattle ranching and subsequent replacement by soy production).[70–72] Land rent is calculated per cell as net present value and defined as follows:

$$\mathrm{NPV}_{\mathrm{cultivation}} = \left(y + r_{\mathrm{gain}}\right) - \left(C_{\mathrm{land}} + C_{\mathrm{transportation}} + C_{\mathrm{eco-certification}} + C_{\mathrm{intensification}} + r_{\mathrm{risk}}\right)/5,$$

where y = yield, r_{gain} = reputational gain for the cultivator from engaging in eco-certification, r_{risk} = reputational risk for the cultivator from engaging in land conversion, and C = various costs.

Largeholders move to the cell with the highest net present value and convert, intensify, or eco-certify the cells depending on which land use option is most profitable. Intensification can only occur on existing cropland and eco-certification only on cells that underwent conversion from forest to cropland prior to a user-defined cutoff time. Smallholders engage in shifting cultivation and fallow their cropland after 2 years. After 5 years, fallows regenerate to secondary forests, and smallholders can return to cells they previously cultivated, thereby creating an informal system of land ownership. Encroachment of protected areas is punishable by a user-defined fine, and large-holder producers and smallholders factor this fine, in combination with the likelihood of being fined, into their land rent calculations. To reflect progress in technology and infrastructure, transportation costs in ABSOLUG decrease over time following a negative logarithmic curve.

We identified parameter values from the scientific literature, expert evaluation, and modeling decisions, and we calibrated these through repeated simulations to reproduce a landscape that experiences substantial deforestation (~90%) over a 40-year simulation period without governance interventions.[30] To verify the model, we conducted code reviews and monitored key variables through extensive testing. The model was evaluated in a two-step process, using scenarios to test operational validity, and local and global sensitivity analyses to assess statistical validity[30] (Figure 5). The sensitivity analyses were conducted in a model configuration that corresponds to the baseline conditions in this study.

Interventions

Weak regulations to accessing to natural resources (weak regulations) and increasing demand for agricultural commodities such as soybeans, rubber, palm oil, or cocoa lead to high rates of deforestation and the creation of tropical forest frontiers.[61,73,74] In past waves of forest frontier expansion in the tropics, well-capitalized private producers with the support of governments were key agents of deforestation.[75] We replicate these dynamics in the weak regulations intervention, where conversion of forest to cropland is not penalized, the government does not pursue a conservation target, and penalties for encroaching riparian buffer zones and illegal acquisition of small-holder land are low and/or infrequently enforced (Table 1). Because tropical land use change in the late 20th and early 21st century has been characterized by the expansion of agricultural frontiers, we consider weak regulations as the baseline against which we compare the other interventions.

Command-and-control interventions are initiated by a government with the aim to achieve environmental goals through land use zoning.[76] They typically display low levels of stakeholder involvement, and their rules and regulations are enforced through penal sanctions or by demonstrating compliance to access resources.[77] Under the command-and-control intervention, the government pursues a target of sparing 30% of the land for conservation and has increased capacity for monitoring and enforcing rules and regulations. Encroachment of protected areas and illegal acquisition of small-holder land is under penalty (Table 1).

Over the past two decades, private actors have increasingly risen to the challenge of removing deforestation from their operations and supply chains through

Parameter	First order Sobol indices	Confidence interval	Total Sobol Indices	Confidence interval	Pearson coefficient
Certification costs	-0.01	0.06	0.21	0.04	-0.05
Set-aside maintenance premium	0.00	0.05	0.17	0.04	0.00
Intensification costs	0.40	0.12	0.58	0.11	-0.22
Pioneer importance of reputation	-0.02	0.05	0.17	0.03	-0.01
Mainstreamer importance of reputation	-0.03	0.06	0.16	0.03	0.01
Laggard importance of reputation	-0.03	0.06	0.16	0.03	0.00
NGO campaigning threshold	-0.01	0.06	0.19	0.05	-0.00
Largeholder lobbying threshold	-0.02	0.05	0.18	0.04	0.00
Government favoring business	0.00	0.06	0.17	0.04	0.01
Government favoring environment	-0.01	0.05	0.17	0.04	0.00
Tier 1 encroachment fine	-0.01	0.06	0.17	0.04	-0.01
Tier 2 encroachment fine	0.01	0.06	0.19	0.04	0.00
Tier 3 encroachment fine	-0.02	0.05	0.17	0.04	0.00
Conservation goal	0.03	0.07	0.23	0.04	0.07
Largeholder lobbying when idle	0.03	0.07	0.24	0.06	-0.01

Figure 5. First order and total Sobol indices (with confidence intervals) and Pearson coefficient for fifteen key model parameters

pledges, participation in eco-certification schemes, or industry-wide operational standards.[9,45] The intrinsic and/or economic motivation of companies is to mitigate reputational risk and secure access to lucrative markets through improving the sustainability of their supply chains and reducing their harmful social and environmental impacts.[78,79] While industry-wide initiatives exist, typically supply chain approaches are limited to individual actors or coalitions of actors.[80] We represent these dynamics in our supply chain sustainability intervention where pioneer largeholders place increased value on their reputation and are thus more likely to engage in eco-certification (reputation preserving and/or enhancing activity) and less likely to engage in land grabbing and encroachment of protected areas (reputation damaging activity). Mainstreamer large-holder producers adopt a similar behavior, albeit at a lower rate than the pioneers. Additionally, pioneer and mainstreamer producers will tolerate higher tax rates on their operation and are less likely to lobby the government (Table 1).

Increasingly, coalitions of public, private, and civil society stakeholders are formed to address deforestation through sustainable development and production approaches, often implemented at the landscape or jurisdictional scale.[13,81,82] Their agendas are set by participating stakeholders, and rules and regulations apply to all actors within the socio-ecological system. The multi-stakeholder coalition intervention combines goals of sustainable production and increased protected area similar to the two previous interventions, albeit to a lesser degree (Table 1). Additionally, CSOs have a lower threshold for campaigning the government to represent increased scrutiny, and laggard large-holder producers show a higher valuation of reputation and are less likely to lobby the government to mimic the idea that multi-stakeholder approaches raise the floor for all actors involved.[12]

Conditions

Capacity of civic and public institutions (institutional capacity) describes the ability of the government to monitor and penalize encroachment of protected areas, illegal appropriation of smallholder-owned land (land grabbing), and to withstand political pressure from largeholders and CSOs in the form of lobbying and campaigning. It also includes the capacity of CSOs to monitor deforestation, engage in shaming efforts against large-holder producers, and to campaign the government. For the government and CSOs, the strong and weak institutions conditions represent high and low capacities respectively (Table 2).

Remaining forest cover at the time of intervention (forest cover) refers to the stage of the forest transition curve at which the intervention is implemented. For example, 10 years into the simulation period, forest cover is high with 77% of the original forest remaining and accelerating deforestation rates like in Cameroon or Peru.[83] Baseline forest cover corresponds to a simulation time of 20 years when forest cover is 50% of the original and still declining, and deforestation rates are decreasing. After 30 years, forest cover is low, and the system has undergone substantial deforestation (26% of original forest cover remaining), and land cover is a mosaic of primary and secondary forests, agroforestry, and annual crops, such as in Côte D'Ivoire or Mato Grosso, Brazil[83] (Table 2).

Stakeholder composition describes proportion of mainstreamer largeholders to pioneer and laggard largeholders. Under baseline condition, six out of ten largeholders are mainstreamers; under pioneer dominant, six out of ten largeholders are pioneers; and under laggard dominant, six out of ten largeholders are laggards (Table 2). This allows us to replicate trends toward corporate consolidation and the resulting dominance by certain types of corporations, e.g., those who place high value on reputation (pioneers) and those focused on expansion of their area under operation (laggards).[84]

Scenario conditions

In the scenario analysis, conditions change over time. The soy scenario is initially characterized by strong institutional capacity, a stakeholder composition dominated by mainstreamer producers, and high forest cover, before it shifts to low institutional capacity in the second simulation. The palm oil scenario initially features medium institutional capacity, a stakeholder composition dominated by laggard large-holder producers, and a medium forest cover, and then it changes to a stakeholder composition dominated by pioneer actors.

Limitations

We simulated conditions and interventions to highlight their archetypal characteristics. In practice, interventions and conditions may not neatly fall into our

Table 1. Description of the governance interventions

Intervention	Key actors	Goal	Theory of change	Attributes
Weak regulations	government, large-holder producers	increase area under production	providing incentives for and removing barriers to expansion of area under cultivation	*
Command and control	government	land sparing for conservation	designation and enforcement of state-owned protected areas	protected area target raised substantially government is proactive encroachment fines doubled
Supply chain sustainability	pioneer large-holder producers	deforestation-free supply chains	intensification and certification of existing crop land; pioneer efforts to be subsequently adopted by other actors	pioneer and mainstreamer valuationof reputation doubled pioneer and mainstreamer lobbying likelihood decreased
Multi-stakeholder coalition	Government, largeholder producers, CSOs	land sparing for conservation, deforestation-free supply chains, socio-economic well-being	agenda is set by all stakeholder groups and rules and regulations apply to all actors in the socio-ecological system; agenda addresses socio-economic issues	protected area target raised moderately encroachment fines increased largeholder valuation of reputation doubled largeholder lobbying likelihood increased

Parameter changes are relative to the *weak regulations* intervention, which serves as a baseline
*The parameter values of the weak regulations intervention serve as the baseline against which the other interventions are compared.

categories and may have fewer pronounced characteristics. We focused on interventions and conditions we deem central to tropical forest frontier systems, but they do not capture all possibilities, including cultural norms, historical contexts, and the availability of resources like time, funding, and expertise. The categorization of producer agents into largeholders (pioneer, mainstreamer, laggard) and smallholders who engage in shifting cultivation is a necessary simplification to control model complexity. A study with a greater focus on smallholders should differentiate between indigenous peoples and local communities versus recent migrants. These two groups are characterized by different levels of place attachment and familiarity with local environmental conditions, which impact forest conversion and conservation.[85–87] Indigenous peoples and local communities are the source of place-based initiatives that influence commodity production and conservation efforts,[88,89] thus impacting the effectiveness and equity of governance interventions beyond what our simulations capture. Expanded versions of the model could represent the contributions of indigenous peoples and local communities to better account for the important role of these stakeholder groups in steering land use sustainability.[90] Further, our study focuses on deforestation, land

Table 2. Description of the seven systemic conditions

Condition	Description	Attributes
Strong institutions	government has high capacity to monitor and enforce illegal deforestation and land grabbing CSOs have high capacities to monitor deforestation rates and apply political pressure to the government (i.e., campaigning)	encroachment detection rate increased government enforcement cadence increased government more resistant to political pressure CSO ability to monitor deforestation rates and campaign increased
Weak institutions	government has low capacity to monitor and enforce illegal deforestation and land grabbingCSOs have low capacities to monitor deforestation rates and apply political pressure to the government (i.e., campaigning)	encroachment detection rate decreased government enforcement cadence decreased government resistance to political pressure decreased CSO ability to monitor deforestation rates and campaign decreased
Pioneer dominant	corporate consolidation among large-holder producers resulting in a greater share of largeholders with high valuation of reputation (pioneers)	total number of largeholders halved number of pioneer largeholders increased number of mainstreamer largeholders decreased
Laggard dominant	corporate consolidation among large-holder producers resulting in a greater share of largeholders with low valuation of reputation (laggards)	total number of largeholders halved number of laggard largeholders increased number of mainstreamer largeholders decreased
High forest cover	by the time of implementation, forest cover and deforestation rates are high	implementation year = 10 forest cover ∼77%
Low forest cover	by the time of implementation, forest cover and deforestation rates are low	implementation year = 30 forest cover ∼50%

Parameter changes are relative to the baseline condition grabbing, and expropriations as indicators for effectiveness and equity, thereby omitting other important aspects of effectiveness and equity, like monetary cost of the interventions, human rights violations, or economic well-being of stakeholders.[91–93] To maintain a manageable level of model complexity, we omitted the financial elements associated with conception, implementation, and operation of governance interventions as well as the dynamics of commodity markets. As a result, we could not evaluate the efficiency of governance interventions in addition to their effectiveness and equity.

AUTHOR CONTRIBUTIONS

All listed authors have read and approved of the final version of this manuscript and have contributed substantive parts to conceptualization, methodology, investigation, formal analysis, data curation, visualization, writing, reviewing, and editing of this work.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

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