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Community forest governance and synergies among carbon, biodiversity and livelihoods

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Forest landscape restoration has emerged as a key strategy to sequester atmospheric carbon and conserve biodiversity while providing livelihood co-benefits for indigenous peoples and local communities. Using a dataset of 314 forest commons in human-dominated landscapes in 15 tropical countries in Africa, Asia and Latin America, we examine the relationships among carbon sequestered in above-ground woody biomass, tree species richness and forest livelihoods. We find five distinct clusters of forest commons, with co-benefits and trade-offs on multiple dimensions. The presence of a formal community management association and local participation in rule-making are consistent predictors of multiple positive outcomes. These findings, drawn from a range of contexts globally, suggest that empowered local forest governance may support multiple objectives of forest restoration. Our analysis advances understanding of institutional aspects of restoration while underscoring the importance of analysing the interconnections among multiple forest benefits to inform effective interventions for multifunctional tropical forests.

The urgency of the twin crises of climate change and biodiversity loss has led to a rapidly growing focus on forest conservation and restoration. Policy advocacy in this context includes proposals for nature-based solutions that can mitigate climate change emissions[1–3] and ambitious targets for a global expansion of protected areas[4,5]. Such policies frequently target rural tropical landscapes, owing to their high biodiversity and carbon sequestration potential[6]. Many forests in these contexts also have substantial human presence[7,8], including an estimated 1.8 billion people that live on lands needed to sustain key biodiversity goals globally[9]. Such human-dominated forest landscapes are integral to rural livelihoods, incomes and well-being[10–12] and play a critical role in helping households respond to climate change stressors[13]. A better understanding of the relationships among multiple benefits such as carbon sequestration, biodiversity conservation and rural livelihoods holds the potential to identify strategic interventions to support rural well-being while helping achieve climate and biodiversity-conservation goals[14–17].

Researchers and policy makers recognize the importance of advancing multiple human and environmental objectives in tandem and taking better account of their interactions, trade-offs and synergies[18–22]. However, many global analyses tend to focus on a specific outcome domain[1,4,5], risking unintended trade-offs and neglecting possible opportunities for co-benefits[15,23–26]. Overall, the relationship between livelihood benefits and other socioeconomic outcomes remains less well understood compared with the large number of studies that examine the links between carbon and biodiversity[27–29]. Despite recent attempts to identify conservation and restoration opportunities globally[1,6,9], careful analyses of the institutional mechanisms that may support co-benefits and multiple positive outcomes, especially at subnational scales, remain rare[30–32]. Informed choices across competing priorities require better knowledge about how interventions targeting one type of outcome affect other outcomes[16,33–35]. Therefore, knowledge of factors associated with different forest outcomes is of central importance in calibrating interventions to minimize trade-offs and enhance co-benefits.

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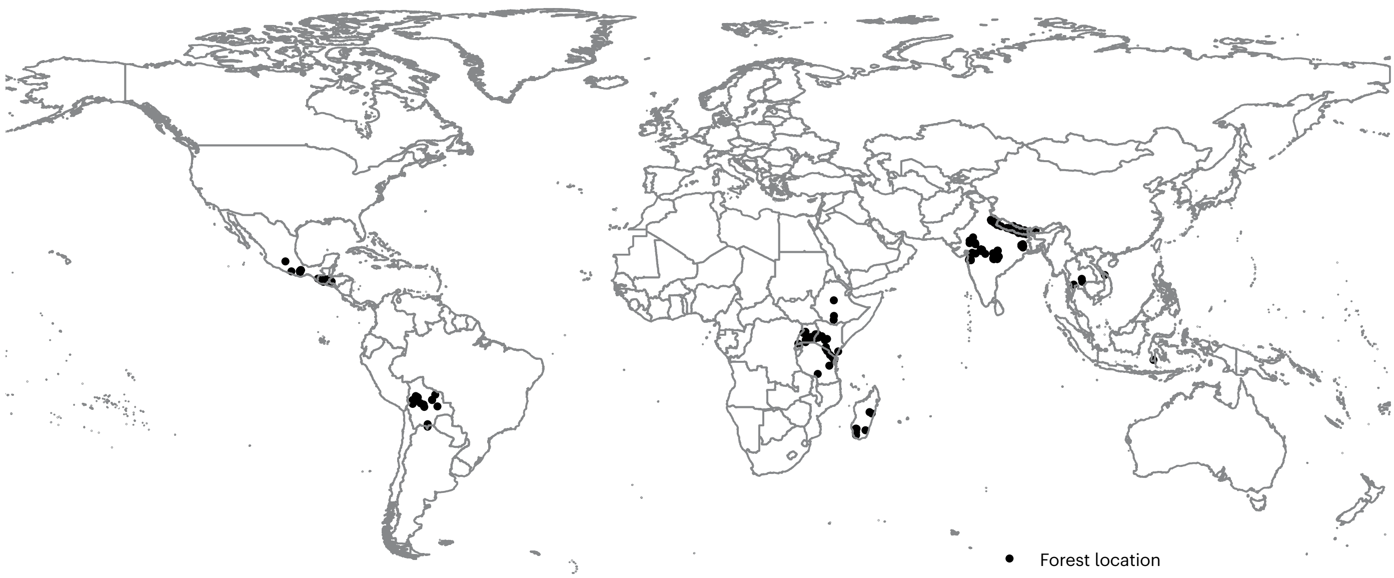

Fig. 1 | Map of study locations. Our study comprises 314 forests in 15 countries in Asia, Africa and Latin America (Supplementary Table 1).

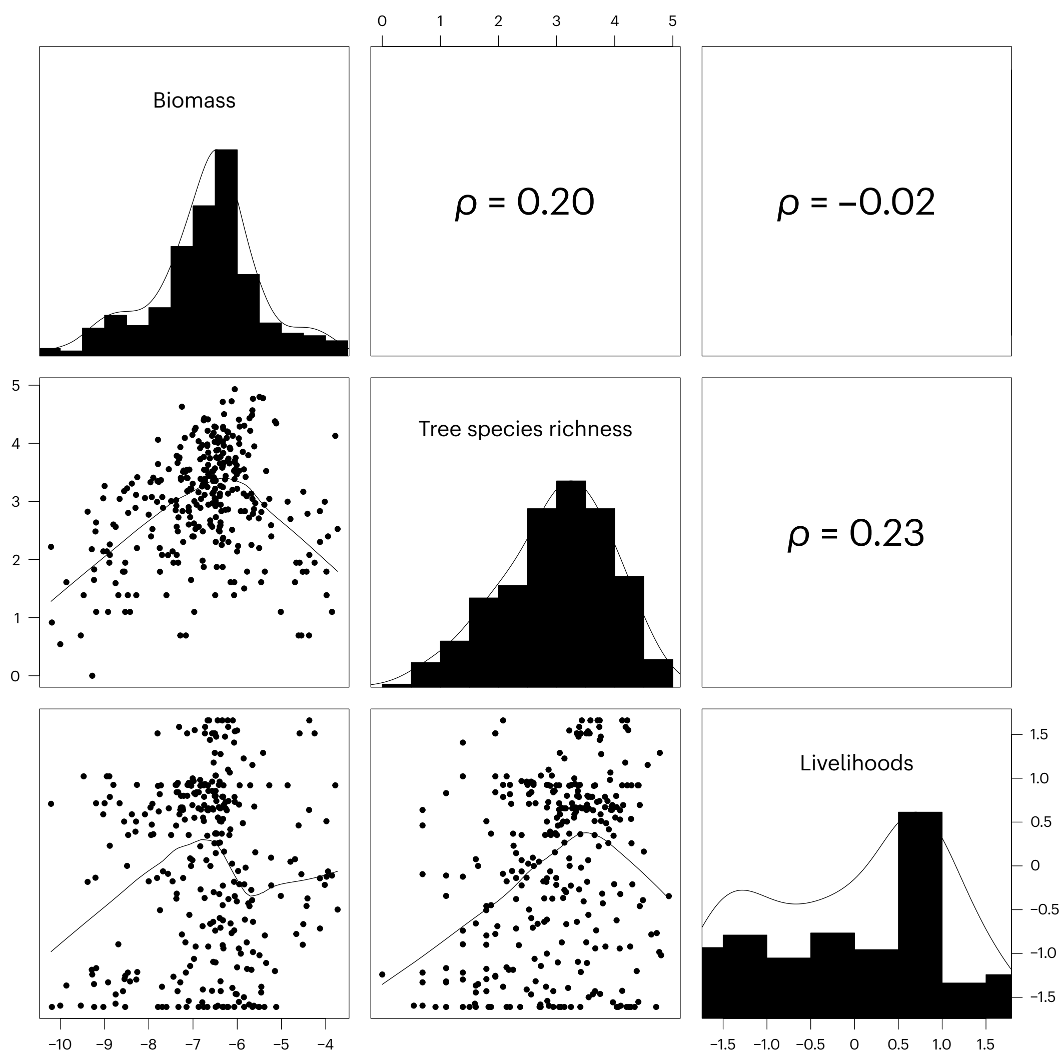

Fig. 2 | Scatterplot matrix of benefits—biomass, tree species richness and livelihoods—of 314 forest commons. Biomass and tree species richness are log-transformed. Spearman's rho for bivariate correlations shows weak associations for biomass–tree species richness ($\rho = 0.1989$; Prob > $|t| = 0.0004$) and livelihoods–tree species richness ($\rho = 0.2268$; Prob > $|t| = 0.0001$) pairs. There is no relationship between biomass and livelihoods ($\rho = -0.0246$; Prob > $|t| = 0.6641$).

To address this need, we analyse a unique dataset of 314 forests in human-dominated landscapes in 15 tropical countries derived from the International Forestry Resources and Institutions (IFRI) research programme (Fig. 1 and Supplementary Table 1). The data have substantial information on local institutions and forestry interventions, thus enabling finer-grained analyses of governance factors associated with different forest outcome combinations across a range of contexts globally. We focus our analysis on forest commons, a class of multiple-benefits forests found extensively in the lower- and middle-income world. Forest commons are used jointly by groups of heterogeneous users, with defined boundaries for the forest and its user group and informal or legal rights to specific forest benefits[36]. Typically, these forests exist as patches in fragmented human-dominated landscapes, and people living in proximity depend on them for such benefits as firewood, timber, fodder and, occasionally, wild honey, mushrooms, medicinal herbs and other non-wood products. Even where governments own forest commons formally, local communities often exercise informal or customary rights of use and management. Given the large population of people that live in and around areas designated as priorities for restoration and conservation globally[8,9], forest commons are likely to play a central role in policy interventions for advancing joint human and environmental benefits within human-dominated landscapes around the world.

Data and analysis

We examine three benefits central to global forest policy debates: contributions to local livelihoods, biomass as a proxy for carbon storage and biodiversity measured as tree species richness. We estimated biomass, an indicator of above-ground carbon stocks, as basal area (m^2 ha^{-1}) of stems, averaged over all trees (diameter at breast height (DBH) > 32 cm) from ~30 randomly selected 10-m-radius plots in each forest. While biodiversity is a complex concept, tree species richness has been shown to indicate a range of other forest taxa[37]. To measure tree diversity, we calculated the Chao1 index of tree species richness for each forest from the list of all trees in ~30 randomly selected plots. We created an index to measure contributions to local livelihoods using factor analysis of the proportions of total firewood, fodder and timber requirements of local users that each forest common supplied. We examine the interrelationship of these three benefits through a hierarchical cluster analysis, which allows us to go beyond bivariate associations with individual outcomes to better understand the trade-offs and synergies between multiple human and environmental objectives.

We analyse three key factors that writings on forest commons have highlighted as predictors of outcomes, and which represent direct avenues for policy intervention in forest commons: formal inclusion, participation and tree plantations. Both formal inclusion and participation are critical elements in forest governance, widely viewed as determinants of restoration success[38–41]. Specifically, we examine the presence of a formal community forest management association and local participation in rule-making as variables representing formal recognition of communities' role in resource management by the national government and the substantive capacity of local actors to influence management decisions in practice. Finally, we consider active interventions for tree plantation, a central focus of global discussions for forest restoration in recent years[1,42] (Supplementary Tables 4 and 5).

Considering these three outcomes—biomass, biodiversity and livelihoods—we find weak positive correlations between biomass and biodiversity (Spearman's $\rho = 0.1989$; Prob > $|t| = 0.0004$) and between livelihoods and biodiversity (Spearman's $\rho = 0.2268$; Prob > $|t| = 0.0001$). There is no statistically significant relationship between biomass and livelihoods (Spearman's $\rho = -0.0246$; Prob > $|t| = 0.6641$) (Fig. 2).

When comparing the relationships between these three forest outcomes and our variables of interest individually—the presence of a formal community forest management association, local participation in rule-making, and interventions for tree plantation—results are mixed. No variable has a significant association with all three outcomes in the same direction (Extended Data Table 1). However, these findings show associations with only one benefit at a time, without respect to the additional benefits that the same forests provide. Hierarchical cluster analysis allows us to study drivers of the three benefits simultaneously.

Drivers of multiple forest outcomes

Hierarchical cluster analysis of the three benefits reveals strong clustering patterns (Supplementary Fig. 3). We identified five distinct clusters in the data, which we have named to describe their dominant characteristics (Fig. 3 and Supplementary Table 3). Multivariate analysis of variance of biomass, tree species richness and livelihoods on the five clusters is highly significant, suggesting a clear demarcation of clusters (Wilks' $\lambda = 0.1088$, $F = 156.44$, Prob > $F = 0.0000$; Lawley–Hotelling trace = 4.8029, $F = 184.31$, Prob > $F = 0.0000$). Here we report general trends in relation to the full sample mean.

The sustainable forests cluster ($n = 119$) has the highest overall levels of the three benefits, with above-average contributions to livelihoods and tree species richness and with biomass values ranging from below average to above average. Notably, the sustainable forest cluster is the largest in our analysis, with 119 forests. By contrast, the degraded forests cluster ($n = 27$) has below-average levels of biomass, tree species richness and livelihoods. Other clusters reveal clear trade-offs. The carbon forests cluster ($n = 23$) has above-average levels of biomass but average livelihoods and below-average tree species richness. The conservation forests cluster ($n = 88$) has average to above-average levels of tree species richness and biomass, but livelihood benefit streams are below average compared with the rest of the sample. Finally, the subsistence forests cluster ($n = 57$) has above-average livelihoods but below-average levels of both biomass and tree species richness.

We turn our attention to the three variables of interest: the presence of a formal community forest management association, local participation in rule-making and interventions for tree plantation. To better understand their relationship with improved benefits from forest commons, we report the marginal effects for predicting cluster membership with respect to the variables of interest through multinomial logistic regressions (Fig. 4 and Extended Data Table 2). The presence of a formal community forest management association is associated with a higher probability that a forest will be a sustainable forest (marginal effects = 0.19, $P < 0.001$), a carbon forest (marginal effects = 0.06, $P = 0.036$) or a subsistence forest (marginal effects = 0.11, $P = 0.007$). It is associated with a lower probability that a forest will be either a conservation forest (marginal effects = −0.28, $P < 0.001$) or a degraded forest (marginal effects = −0.08, $P = 0.034$). Local participation in rule-making is associated with a higher probability that a forest will be either a carbon forest (marginal effects = 0.08, $P = 0.007$) or a subsistence forest (marginal effects = 0.16, $P < 0.001$) and a lower probability that it will be a conservation forest (marginal effects = −0.29, $P < 0.001$). Finally, tree plantations are associated with a higher probability that a forest will be a sustainable (marginal effects = 0.19, $P < 0.001$) or a subsistence forest (marginal effects = 0.24, $P < 0.001$) and a lower probability it will be a carbon (marginal effects = −0.11, $P < 0.001$) or conservation forest (marginal effects = −0.37, $P < 0.001$).

Decision-makers seek to avoid multiple negative outcomes in forests. Relative to being a degraded forest, a community management association increases the odds that a forest will be a sustainable forest (relative risk ratio (RRR) = 4.06, $P = 0.002$), a carbon forest (RRR = 5.94, $P = 0.008$) or a subsistence forest (RRR = 4.69, $P = 0.002$). Likewise, local participation in rule-making increases the odds that a forest will be a carbon forest (RRR = 5.24, $P = 0.01$) or a subsistence forest (RRR = 4.07,

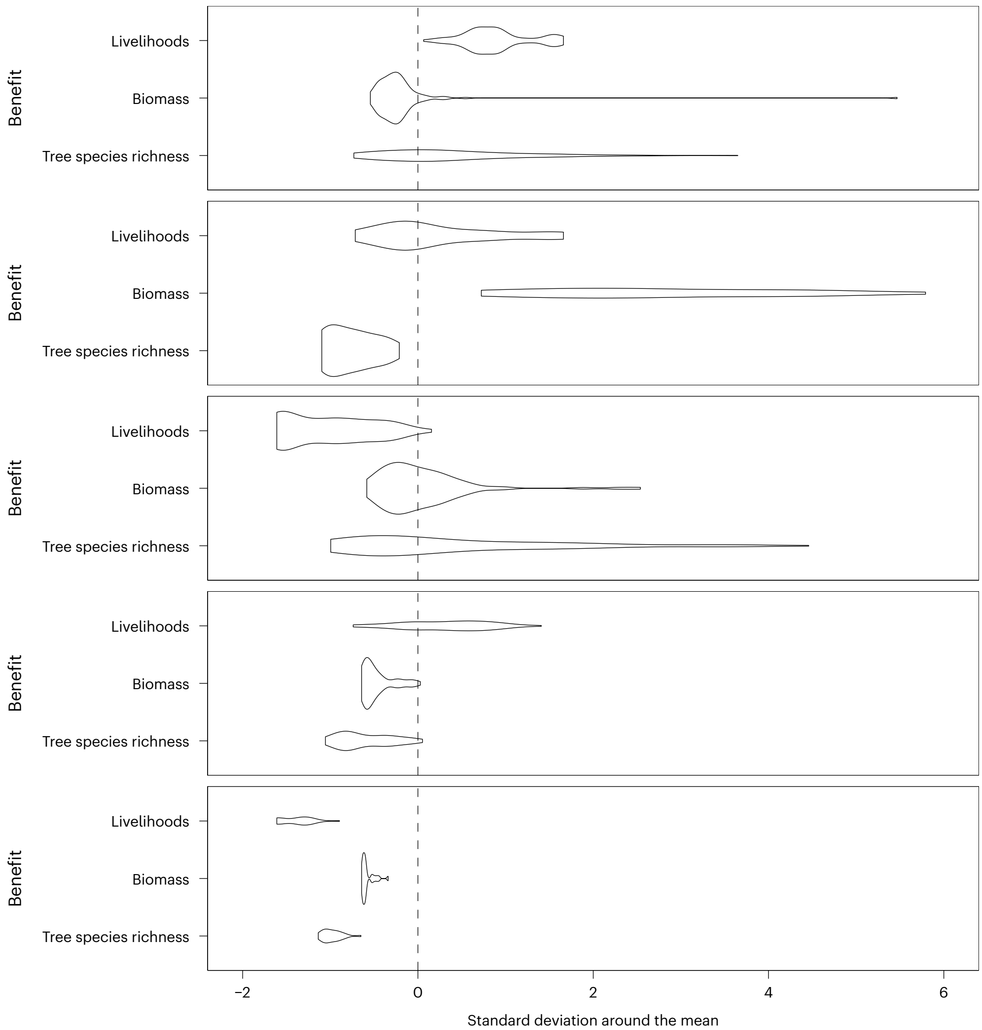

Fig. 3 | Clustered forest outcomes for biomass, tree species richness and livelihoods. The 314 forests in the dataset are classified into five clusters (from top to bottom): sustainable forests, carbon forests, conservation forests, subsistence forests and degraded forests. The three benefits were log-transformed and standardized before cluster analysis. The *x* axis shows standard deviation around the mean. Three of the clusters (carbon, conservation and subsistence forests) privilege one of the three benefits, while two clusters represent multiple positive (sustainable forests) and negative (degraded forests) outcomes across the three benefits.

$P = 0.004$) rather than a degraded forest (Fig. 5 and Extended Data Tables 3 and 4).

By contrast, tree plantations show an opposite direction of association. Tree plantations are associated with reduced odds that a forest will be a carbon forest (RRR = 0.05, $P < 0.001$) or a conservation forest (RRR = 0.09, $P < 0.001$) relative to a degraded forest (Fig. 5 and Extended Data Tables 3 and 4).

Discussion

Contemporary crises of climate change and biodiversity loss have led to global calls for policy action to protect and restore forests around the world. Because a large proportion of the world's population depends on forest resources for basic livelihood benefits, supporting the well-being of rural and indigenous communities remains a central forest policy objective[17,20,43]. As policy efforts have expanded beyond a focus on strict conservation areas to landscapes with substantial human presence, interventions need to account for the relationships between diverse human and environmental benefits that different landscape patches provide. To achieve this goal, it is necessary to move beyond analyses that treat different forest management objectives as discrete outcomes to better understand their interconnections. We suggest that our approach—a cluster analysis of multiple forest benefits—can serve as a useful foundation to better understand the relationships among conflicts, co-benefits and drivers of different benefit combinations.

Our analysis, spanning forest commons in 15 countries globally, affirms that forests used and managed by indigenous and rural communities often support global environmental objectives such as carbon and biodiversity alongside rural livelihood needs[11,39,44–46]. Yet while we observe synergies, the distribution of outcomes in our data suggests that trade-offs are common in many contexts. Given the increasing fragmentation of forests globally[47], there is a need to move beyond expectations of 'win–win' outcomes and overarching 'best practice' principles that focus primarily on jointly positive outcomes[38,48,49]. Knowledge of how benefits vary on multiple dimensions holds the potential to design policy interventions that better catalyse the real-world benefit potential of different forest patches and to improve aggregate outcomes across broader landscapes[16,22,50,51]. We caution that the associations we find in our data are not necessarily causal. Yet an important aspect of our approach and analysis is to show that these associations emerge from a large global sample, thus paving the way for more context-sensitive analyses at national and subnational scales.

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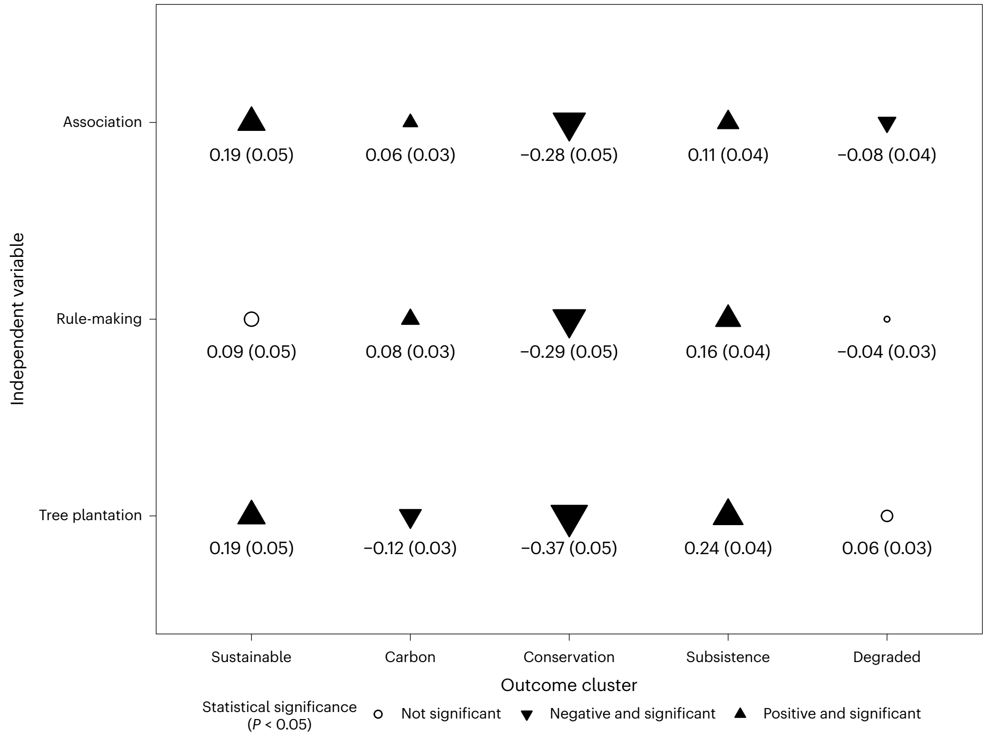

Fig. 4 | Drivers of multiple benefits from forest commons. Marginal effects of known drivers of forest outcomes in 314 forest commons. The figure shows results of bivariate multinomial logistic regressions of each independent variable (*y* axis) on each of the five clusters. Coefficients are presented with standard errors in parentheses. The upward-pointing triangle represents a positive and significant effect, and the downward-pointing triangle represents a negative but significant effect. The hollow circles imply insignificant associations. The sizes of the triangles and circles correspond to the values of marginal effects from the regression; the larger the size of the shape, the greater is the change in probability of the outcome cluster for a one-unit change in the independent variable (Extended Data Table 2).

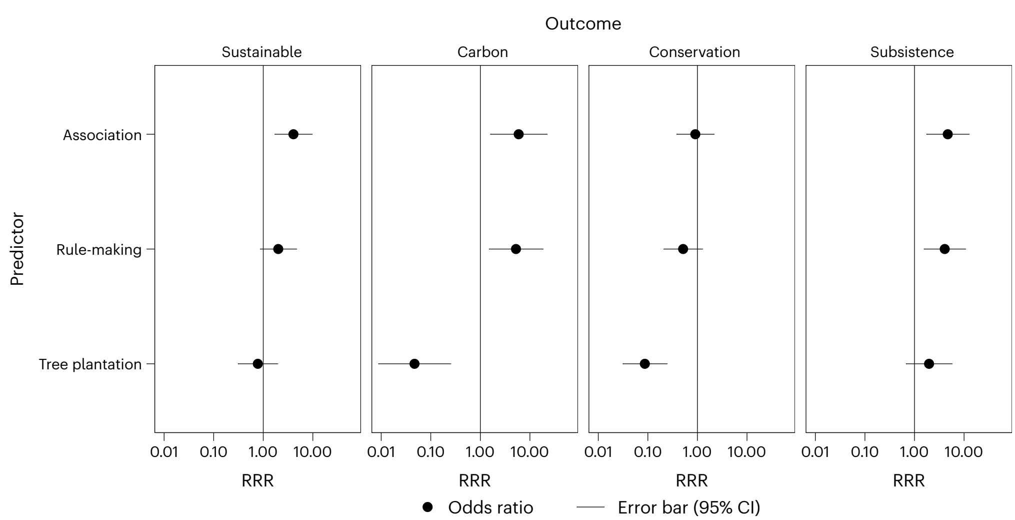

Fig. 5 | Avoiding negative outcomes in forest commons. Odds (RRR for one-unit change in the independent variable) of avoiding negative outcomes in 314 forest commons. The presence of a formal association of local users increases the odds of being a sustainable, carbon or subsistence forest compared with a degraded forest. Local participation in rule-making increases the odds of being a carbon or subsistence forest compared with a degraded forest. By contrast, tree plantation activity decreases the odds for carbon and subsistence forests compared with degraded forests (Extended Data Table 4).

Our analysis raises questions about some general forest policy prescriptions. Tree planting has been advocated as a key carbon mitigation priority globally[1,49]. Tree planting may be valuable to achieve mitigation goals, but it is necessary also to attend to its social–environmental risks identified in growing research[34,52]. Risks stem in part from the incentive structures of many forest bureaucracies that prioritize measurable targets for aggregate trees planted and from unintended social consequences of displacement of lives and livelihoods[53]. We find tree plantations to be positively associated with subsistence and sustainable forests but negatively associated with carbon and conservation forests. Compared with degraded forests, tree plantations decrease the relative odds of being either a conservation or a carbon forest and have no significant association with sustainable or subsistence forests. These heterogeneous associations suggest that in many contexts around the world, existing tree-planting practices may not be sufficient to restore degraded forests in support of multiple human and environmental objectives. Our work adds to a growing chorus of scholars emphasizing the need to ensure that tree planting is implemented in a locally responsive manner and with specific attention to the needs of local forest users[34,43].

Indeed, our work suggests that governance conditions may be more important to encourage multiple desired outcomes from forests. Compared with tree planting, institutional factors show strong associations with joint positive outcomes in our analysis. These findings align with recent work that argues for the need to move beyond the present global emphasis on tree planting as a primary means for forest restoration[34,54]. Institutional reforms that support more effective local resource management have the potential to serve as an important policy strategy for supporting multiple human and environmental outcomes from forest restoration.

Recent analyses have argued for the importance of local participation to support forest restoration and nature-based climate solutions[49,55–57]. Our results provide additional insight into the kinds of institutional features that may bolster the positive effects of local participation. Our most striking finding is that empowered local governance—in the form of formal community forest management organizations and local participation in rule-making—is a key predictor of multiple positive outcomes. This finding aligns with a well-established body of research on how local actors possess a comparative advantage for coordinating local governance functions[58,59]. Compared with external actors and government agencies, local actors have detailed place and time-specific knowledge of socioecological dynamics and can devise more locally appropriate use and monitoring rules[40,41,60]. Existing research shows that decentralizing management authority to communities can support more-effective, locally driven governance processes over the long term[32,39,60]. Our work advances these discussions by providing evidence that the formal involvement of communities in governance can help to support positive benefits for carbon, biodiversity and rural livelihoods simultaneously, and that this is likely to be true across a diversity of global contexts.

Our analysis and results are particularly salient in light of growing calls for recognition of the rights and involvement of indigenous peoples and local communities in contemporary climate mitigation and restoration interventions[34,61,62]. Importantly, our focus on formal local governance moves beyond more general calls for 'stakeholder participation' common in existing research[38,49,57]. In our analysis, a community management association implies formal legal recognition of local management authority by the state, while participation in rule-making reflects the substantive ability of local stakeholders to influence management decisions in accordance with time- and place-specific knowledge. Indeed, formalized institutions can promote more effective local forest governance in several ways: helping to ensure a measure of local autonomy, providing channels to access technical support from the state and establishing a clear procedural basis for the selection and replacement of authority—thus improving accountability of power-holders to rural interests[63–65]. A core implication of our work is that to create favourable conditions for advancing multiple benefits, there is a need to move beyond structured stakeholder consultations and project-based participatory forums to build more durable and empowered local institutions that can enable socioecological benefits over the long term[43,66].

Importantly, formalized local forest institutions come in many different forms, and there is no one-size-fits-all approach that can be applied globally[67]. Research shows that even in the context of policies for decentralized forest governance, communities' ability to achieve meaningful influence is highly variable[68,69], and that the success of local forest management also depends on support from professional forest administrators[63,70]. Accordingly, further work is needed to better understand how diverse national- and subnational-level policy arrangements enable or impede the success of empowered local governance as a tool for achieving just climate action and other forest restoration goals[65,71]. For example, it would be possible to test which specific aspects of governance may be more important, the ways these change as communities gain more experience with decentralized forest management and how they interact with other socioeconomic and environmental factors to influence multiple outcomes at the landscape level.

Amidst growing global calls for nature-based climate solutions and expanding protected areas for biodiversity conservation, it is important to recognize that forests in much of the world have a substantial human presence and are thus multifunctional in nature. In many human-dominated landscapes, it is neither feasible nor ethically desirable to ignore the needs of rural populations[34], who have also played an important role in helping to support broader environmental objectives in many contexts[46,62]. Forest commons, used and managed by rural communities as part of a broader landscape matrix, have much to offer in advancing diverse human and environmental goals, and indeed, many are already being managed in an effective and cost-effective manner[60,63,72]. Our analysis suggests that giving rural and indigenous communities formal, legally recognized opportunities to engage in local management practices is not just normatively desirable but may serve as an important step to advance multiple human and environmental benefits in forested landscapes around the world.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-023-01863-6.

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Methods

IFRI research programme sampling approach, methods and case selection

Founded in 1992, the IFRI research programme is a network of collaborative research centres across North and South America, Africa, Asia and Europe. The networked research centres focus on case studies and analyses of local forest governance and forest resource outcomes in diverse sociopolitical, ecological and institutional contexts. Their goal is to use the data they have collected to understand the factors that shape long-term sustainable management of forest commons.

IFRI sites are broadly representative of forests in human-dominated landscapes throughout the tropics that are outside of the three large contiguous tropical forest areas that are perhaps most well known (Congo Basin forests in Central Africa, forests in the Amazon Basin across nine Latin American countries, and Borneo across Indonesia and Malaysia). IFRI sites consist of fragmented and typically smaller forest patches embedded in agricultural matrices and with varying but generally high population density and relatively low-income populations. Research sites are selected to be representative of the range of forest management regimes that exist in each country, to ensure variation on hypothesized causal variables, and with a clear knowledge that sites must not be selected on the basis of our primary outcome of interest—the condition of the forests. Sampling methods for forest vegetation and forest-based livelihoods followed the IFRI methodology[73], a comprehensive set of research instruments for collecting social–ecological data at the local level. The research protocols employ vegetation plot measurements in forests to obtain information on characteristics of forest structure and species composition, and semi-structured interviews and focus-group discussions with forest users and village, district and/or state authorities involved in forest management.

The dataset used for this analysis was drawn from the October 2018 compiled version of the full IFRI database covering 1,028 forests and villages in 26 countries. Our criteria for case selection from the IFRI database excluded forests outside of the low-income tropics (that is, cases from the USA and Japan), forests less than 5 ha and those with absent plot vegetation data. In cases where a forest had longitudinal data, we used the visit date with the most recent plot data available. This resulted in a sample of 314 in 15 countries across Asia, Africa and Latin America (Fig. 1 and Supplementary Table 1).

Selection bias and associated limitations

The forests in our analysis do not constitute a random sample. Therefore, care should be taken before generalizing the results. Given the lack of records and documentation regarding the nature, occurrence, spread and extent of forests in developing countries, it is impossible to draw a fully random sample from the universe of cases. We have taken all necessary care to ensure that the sample is not skewed on relevant dimensions, including those not included in our statistical model. The possibility of selection bias could be taken to imply that our statistical inferences are not generalizable beyond the sample. By contrast, we suggest that because the cases were selected without a deliberate focus on outcomes, the conclusions are generalizable for the range of values of the independent variables in our data.

Ethics

As a global research programme, data were collected and pooled into IFRI by collaborating research centres, each of which followed laws and ethical regulations in its country. Data for this paper are aggregated and contain no personally identifying information. IFRI has received review from institutional review boards, most recently University of Michigan IRB, ID: HUM00092191.

Benefits from forest commons

Biomass. For each forest in our data, forest vegetation and biophysical data were collected in ~30 plots of 10 m radius (314 m^2) randomly distributed across the forest. Local and botanical names of each tree found in the circle are identified and recorded along with their girth at breast height. We calculated the basal area of trees with a diameter greater than 10 cm at breast height. We summed the basal areas of all trees in a plot to calculate basal area per square metre at the plot level and then averaged the values across all the plots in a forest.

Biodiversity. We use the non-parametric Chao1 estimator of tree species richness[74] as a proxy indicator for overall forest biodiversity. For each forest, we conducted 100 randomized runs on the plot abundance data for tree stems, summarized by species, to generate 95% confidence intervals around the mean of Chao1. Trees refer to stems with >31.4 cm girth at breast height, excluding woody climbers. The concept of biodiversity encompasses much complexity, and tree species richness does not capture all facets of this phenomenon. Although an imperfect proxy for overall biodiversity, tree species richness has been shown to be a viable indicator for several other well-studied forest taxa[75,76].

We calculated Chao1 using the software programme EstimateS[77]. EstimateS is designed to assess and compare the diversity of species composition on the basis of the sample data. The term 'sample' refers to a list of species from random forest plots. For estimating the Chao1 estimator of species richness, counts of individuals for each species were recorded in each of a set of samples (called sample-based abundance data). EstimateS allows for both single and multiple datasets as inputs. Given the structure of the ecological data collected using IFRI plot instruments, data were first organized as a single dataset consisting of sample-based abundance data. Each data file represents a forest with the number of random plots as several (1–30) related samples that feature abundance data for unique species recorded in the forest.

The data input 'filetype' and format were selected after launching EstimateS to complete loading the dataset correctly. The estimated number of species in a forest, given the observed number of species, is reflected in the output table. The Chao1 estimator of species richness is based on the concept that most information about the number of missing species can be inferred from the rare species in the sample. Therefore, Chao1 uses only singletons and doubletons to estimate the count of missing species and is represented in the following form.

$$\hat{S} = D + f_1^2/2f_2$$

(OR)

$$\hat{S}_{\mathrm{Chao1}} = S_{\mathrm{obs}} + \left(\frac{n-1}{n}\right)\frac{F_1^2}{2F_2} \quad \text{(classic)}$$

$$\hat{S}_{\mathrm{Chao1}} = S_{\mathrm{obs}} + \left(\frac{n-1}{n}\right)\frac{F_1(F_1-1)}{2(F_2+1)} \quad \text{(bias-corrected)}$$

where $\hat{S}$ = total number of estimated species in a community, S_{obs} = observed number of species in the sample, F_1 = number of species that are represented exactly once in the sample (singletons), F_2 = number of species that are represented exactly twice in the sample (doubletons), n = sample size and D = number of distinct species discovered in the sample.

The $\hat{S}$ values range from 1 to 138.5. For our analysis, we excluded observations with species index greater than 140.

Livelihoods. The variables used for computing the livelihoods index—sfodder (settlement dependence on fodder), sfuelwood (settlement dependence on fuelwood) and stimber (settlement dependence on timber)—are drawn from features in the data that capture the percentage of the needs of the residents in the settlement that are supplied by the forest. The IFRI training manual describes two methods to capture this data: through focus-group discussions conducted at the settlement level and through personal interviews of key persons. The sampling method employed to identify key informants for personal interviews is snowball sampling. For the focus-group discussion, the interviewing Collaborative Research Center ensures that there is participation of individuals from diverse social groups in the settlement. The data are collected for each settlement and then aggregated to the forest level. A forest may be associated with one or more settlements.

We used principal component analysis to identify the factors, or the principal components, that best explain the pattern of community dependence across 314 forests for livelihoods. The first factor has an Eigen value of 1.77, which meets the (Kaiser) criterion for retaining a factor and explains 59.17% of the variability (LR test: independent versus saturated: $\chi^2(3) = 237.11$; Prob > $\chi^2 = 0.0000$). The Eigen values of factor 2 and factor 3 are less than 1 and hence are not retained. We also calculated the Cronbach's alpha to test the reliability and internal consistency of the livelihoods index (average inter-item covariance: 510.015; scale reliability coefficient: 0.613). The livelihoods index correlates highly with the Cronbach's alpha score (Spearman's rho = 0.9669; Prob > $|t| = 0.0000$), and the results are identical (Supplementary Table 2).

Drivers of biomass, biodiversity and livelihoods

Our dataset includes the preceding three benefits from forest commons—biomass, biodiversity and livelihoods. We also analysed three variables that writings on forest commons have highlighted as predictors of outcomes and which also represent avenues for policy intervention (Supplementary Tables 4 and 5). Association is a binary variable representing forests owned or managed by a formal association of users under national law. We define rule-making as effective and meaningful participation of local communities in making formal rules regarding governance of the forest. We define a forest as having meaningful participation in rule-making if the power to make formal rules to govern the forest lies with the local association, the local government or a local non-government body. Association and rule-making are orthogonal and capture different institutional aspects of forest governance. For example, an association could exist and perform various management roles but lack influence over rules, while for another forest, local communities might be participating effectively through an informal institution. Tree planting is also a dichotomous variable that indicates that tree planting has been carried out in the past ten years.

We tested for pairwise strength of associations between the three benefits and the variables we study (Supplementary Fig. 2 and Extended Data Table 1). In general, we found that these variables are either not significantly associated with or negatively associated with biomass and tree species richness, and positively associated with livelihoods. However, the strength of association is generally weak (with the exception of tree plantation and biomass). This suggests that some trade-offs among forest benefits may be inevitable. However, these findings show associations with only one benefit at a time, without respect to other benefits that a forest provides. We undertook a cluster analysis to study the three forest benefits simultaneously.

Cluster analysis

Using wards-linkage hierarchical clustering, we generated nested classes for 314 forests with biomass, biodiversity and livelihoods as the component dimensions. Forests that exhibit similar characteristics are grouped together into one cluster on the basis of the three dimensions. In hierarchical clustering, the two closest observations in the sample of N observations are merged into one group, producing $N-1$ total groups. The two closest groups/observations are then merged so that there are $N-2$ total groups. This process continues until all the 314 observations are merged into one large group, producing a hierarchy from one large group to five groups in this case (Supplementary Fig. 3 and Supplementary Table 3).

Therefore, each cluster has observations that are similar to each other with respect to biomass, biodiversity and livelihoods and dissimilar to forest commons in the other four clusters on the three dimensions. We have given the clusters names that describe their dominant characteristics on these three outcomes. The names are thus descriptive and do not refer to specific legal or customary categories. Sustainable forests have the highest overall levels of the three benefits, with above-average contributions to livelihoods and tree species richness and with biomass values ranging from below average to above average. Carbon forests have above-average levels of biomass, average livelihoods and below-average tree species richness. Conservation forests have average to above-average levels of tree species richness and biomass, but livelihoods are below average. Subsistence forests have above-average livelihoods but below-average levels of both biomass and tree species richness. Finally, degraded forests have below-average levels of all three outcomes compared with the rest of the sample (Fig. 3).

Models and analysis

The analysis was implemented using multinomial logistic regression. We ran a series of pairwise regressions using each explanatory variable to test association with each cluster. The results provide us with a comparative assessment of the strength of each variable in predicting membership in the clusters (Extended Data Tables 2–4). Given the small sample, we tested for a number of violations of the assumptions of the model. The final models were resilient to a series of postestimation tests. Likelihood ratio tests for independent variables (Ho: $B = 0$) and Wald tests for simple and composite linear hypotheses about individual parameters with a Bonferroni adjustment were not significant for any of the models. Standard errors calculated using the Huber–White sandwich estimator (with and without clustering on country) did not produce significantly different results. We also implemented the Hosmer–Lemeshow goodness-of-fit test for multinomial logistic regression models[78]; all our models report a good fit. Model parameters and coefficients were used to compute marginal effects of the change in one unit of the explanatory variables on each cluster (Extended Data Table 2) as well as the relative risk ratios for selected explanatory variables, with degraded forests as the base category for comparison (Extended Data Table 4 and Fig. 5).

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The dataset used for this analysis is publicly available at Mendeley Data[79].

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Author contributions
H.W.F., A.C., A.D., N.P. and A.A. analysed the data, and H.W.F., A.C. and A.A. wrote the manuscript. A.A. designed the research. A.D. and N.P. processed and analysed the data.

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The authors declare no competing interests.

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Extended Data Table 1 | Spearman's Rank Correlation of selected variables and individual forest outcomes

Variable	Human/environmental benefit	Spearman's Rho	Prob > |t|
Association	Biomass	-0.0166	0.7699
	Tree Species Richness	-0.0827	0.1439
	Livelihoods	0.2712	0.0000
Rulemaking	Biomass	-0.1436	0.0109
	Tree Species Richness	-0.2026	0.0003
	Livelihoods	0.1844	0.0010
Tree plantation	Biomass	-0.4385	0.0000
	Tree Species Richness	-0.1936	0.0007
	Livelihoods	0.2295	0.0001

Spearman's Rank Correlation between 'Association', 'Rule making', and 'Tree plantation' the three benefits from forest commons individually.

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Extended Data Table 2 | Marginal effects on probability of clustered forest outcomes

	N	Sustainable	Carbon	Conservation	Subsistence	Degraded
Association	314	0.192	0.057	-0.282	0.111	-0.078
		(0.054)	(0.027)	(0.055)	(0.042)	(0.037)
Rulemaking	314	0.092	0.077	-0.289	0.158	-0.038
		(0.054)	(0.029)	(0.049)	(0.042)	(0.032)
Tree plantation	301	0.194	-0.118	-0.373	0.236	0.061
		(0.055)	(0.029)	(0.047)	(0.043)	(0.032)

Marginal Effects of unit change in independent variables on the probability that a forest belongs to a specific cluster (standard errors in parentheses).

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Extended Data Table 3 | Regression results against 'Degraded Forests'

Variable	N	Sustainable	Carbon	Conservation	Subsistence
Association	314	1.402	1.781	-0.098	1.545
		(0.444)	(0.673)	(0.443)	(0.506)
Rulemaking	314	0.697	1.656	-0.664	1.404
		(0.433)	(0.640)	(0.461)	(0.494)
Tree Plantation	301	-0.252	-3.056	-2.437	0.677
		(0.470)	(0.857)	(0.524)	(0.544)

Regression Results (Standard Errors in parentheses), with base outcome = 'Degraded Forests'.

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Extended Data Table 4 | Relative risk ratios of avoiding 'Degraded Forests'

Variable	N	Sustainable	Carbon	Conservation	Subsistence
Association	314	4.062	5.937	0.906	4.687
		(1.801)	(3.994)	(0.402)	(2.369)
Rulemaking	314	2.007	5.236	0.514	4.072
		(0.870)	(3.348)	(0.237)	(2.011)
Tree plantation	301	0.777	0.047	0.087	1.968
		(0.365)	(0.040)	(0.046)	(1.072)

Relative Risk Ratios (standard errors in parentheses), with base outcome = 'Degraded Forests'. Each ratio represents the relative odds of each cluster compared to Degraded Forests for a one-unit change in the independent variables.

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Software and code

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Data collection	No software was used for data collection
Data analysis	Data was analyzed using STATA version 15.

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Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	All data on human forest use patterns is aggregated to the user group and therefore not disaggregated by gender. Data reflects both women and men's forest use patterns.
Population characteristics	Similarly, the data is not disaggregated across different social groups. Please see information about research design below.
Recruitment	There was no recruitment of individual research subjects.
Ethics oversight	The IFRI research program has been reviewed by institutional review boards, most recently University of Michigan IRB, ID: HUM00092191.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

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Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This analysis uses data collected through the International Forestry Resources and Institutions (IFRI) research program, a network of collaborative research centres in North and South America, Africa, Asia, and Europe. The data is quantitative, drawn from case studies of forest governance and forest resource outcomes in diverse socio-political, ecological, and institutional contexts. The research seeks to understand the factors that shape long term sustainable management of forest commons.
Research sample	The data for this analysis comprises 314 forest commons in 15 tropical countries. IFRI sites are selected to be broadly representative of forests in human-dominated landscapes throughout the tropics that are outside of the three largest contiguous tropical forest areas (Congo Basin forests in Central Africa, forests in the Amazon Basin across nine Latin American countries, and Borneo across Indonesia and Malaysia). IFRI sites consist of fragmented and typically smaller forest patches embedded in agricultural matrices, with varying but generally high population density and relatively low-income populations.
Sampling strategy	Research sites are purposefully selected to be representative of the range of forest management regimes that exist in each country, to ensure variation on hypothesized causal variables, and with a clear knowledge that sites must not be selected on the basis of our primary outcome of interest – the condition of the forests.
Data collection	Sampling methods for forest vegetation, forest-based livelihoods, and forest governance followed the IFRI Methodology, a comprehensive set of research instruments for collecting social-ecological data at the local level. The research protocols employ vegetation plot measurements in forests to obtain information on characteristics of forest structure and species composition, and semi-structured interviews and focus group discussions with forest users and village, district and/or state authorities involved in forest management. Full information about methods and survey instruments can be accessed here: http://ifri.forgov.org/resources/methods/
Timing	IFRI was founded in 1992. The analysis includes data collected between 1993 and 2016, with a median year of 2008. In cases where a forest had longitudinal data, we used the visit date with the most recent plot data available.
Data exclusions	Our sample of 314 forest commons in 15 tropical countries was drawn from the October 2018 compiled version of the full IFRI Database. Criteria for case selection from the IFRI Database excluded forests outside of the low-income tropics (i.e., cases from the USA and Japan), forests less than 5ha, and those with absent plot vegetation data.
Non-participation	Individuals in the communities using the forests in our sample were interviewed as Key Informants with specialized knowledge or as part of Focus Group Discussions. In either case, no personally identifiable information was collected on any of the individuals. Questions for data collection were always focused on the aggregate, with information collected at the Settlement, User Group, or Organization levels.
Randomization	Given the lack of records and documentation regarding the nature, occurrence, spread, and extent of forests in developing countries, it is impossible to draw a fully random sample from the universe of cases. We have taken all necessary care to ensure that the sample is not skewed on relevant dimensions, including those not included in our statistical model. The possibility of selection bias implies that our statistical inferences are not generalizable beyond the sample. Rather than reaching such an extreme conclusion, we suggest

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