One Earth

CellPress
OPEN ACCESS

Perspective

Sustainable forest transitions: A new analytical framework to understand social and ecological outcomes of reforestation

Johan A. Oldekop,[1,*] Katie Devenish,[1] Lucas Alencar,[1] James T. Erbaugh,[2,3] Mariana Hernández-Montilla,[1] Sreeja Jaiswal,[4,5] Duong T. Khuu,[1] Stephanie Mansourian,[6,7,8] Patrick Meyfroidt,[9,10] Sandy Nofyanza,[1] and Rose Pritchard[1]

[1]Global Development Institute, University of Manchester, Manchester, UK
[2]Department of Environmental Studies, Dartmouth College, Hanover, NH, USA
[3]Global Science, The Nature Conservancy, Arlington, VA, USA
[4]Alfred Weber Institute for Economics, University of Heidelberg, Heidelberg, Germany
[5]Climate Economics and Policy – MCC Berlin, Potsdam Institute for Climate Impact Research, Berlin, Germany
[6]Mansourian.org, Crassier, Switzerland
[7]Institute of Geography and Sustainability, University of Lausanne, Lausanne, Switzerland
[8]Department of Social Sciences, University of Geneva, Geneva, Switzerland
[9]Earth and Life Institute, UCLouvain, Louvain-La-Neuve, Belgium
[10]Fonds de la Recherche Scientifique F.R.S.-FNRS, Brussels, Belgium
*Correspondence: johan.oldekop@manchester.ac.uk
https://doi.org/10.1016/j.oneear.2025.101248

SUMMARY

Restoring forests is key to addressing the climate and biodiversity crises and can benefit forest-dependent communities. However, frequent social and ecological trade-offs between these goals pose significant challenges for forest restoration efforts. Our understanding of how to maximize positive social and ecological restoration outcomes is hindered by the absence of a social-ecological theory of forest restoration. We present a new analytical "sustainable forest transitions" framework to study the joint social and ecological outcomes of reforestation drivers. Our framework advances forest transition theory, the main existing framework for understanding reforestation drivers, by incorporating social outcomes and a wider set of ecological outcomes, paying particular attention to interactions between drivers and the sociopolitical contexts in which they operate. Advances in data availability, computing power, and causal inference methods allow our framework to be operationalized. Doing so could inform forest restoration actions that maximize benefits for climate, biodiversity, and forest-dependent communities.

INTRODUCTION

Restoring forests is key to addressing the climate and biodiversity crises[1,2] and supporting the sustainable development of Indigenous peoples and local communities (IPLCs).[3–5] Key international sustainability agreements, including the United Nations (UN) Sustainable Development Goals,[6] the Paris Agreement,[7] the Bonn Challenge,[8] the New York Declaration on Forests,[9] and the UN Decade on Ecosystem Restoration[10] emphasize the importance of forest restoration in addressing current environmental problems. The new Global Biodiversity Framework of the Convention on Biological Diversity also includes a target to ensure that 30% of degraded ecosystems globally are under effective restoration by 2030.[11] These agendas have catalyzed unprecedented political and financial commitments to reverse forest declines and calls to prioritize forest-dependent communities.[12,13]

Forest restoration efforts face formidable challenges, however, particularly in meeting the scale and scope of these ambitious global targets.[14] Diverse actors within the global forest restoration movement prioritize different but interrelated goals or dimensions[5,15–17] (Figure 1): (1) social, economic, and political benefits, equity and secure land and resource rights for IPLCs living on lands undergoing reforestation and (2) environmental benefits that maintain or enhance biodiversity and mitigate climate change by sequestering carbon. Critically, to meet these objectives, restoration needs to be long-lasting and should not displace deforestation to other regions. However, frequent trade-offs between social and environmental goals have posed significant challenges for the design and implementation of forest restoration efforts at scale.[15,18]

To design effective forest restoration interventions, improved frameworks, theories, and models that combine an understanding of where and why forest gains occur with their associated social and ecological outcomes is essential. However, such knowledge is hindered by the fragmentation of research across disciplines,[19] including (1) ecology, which

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

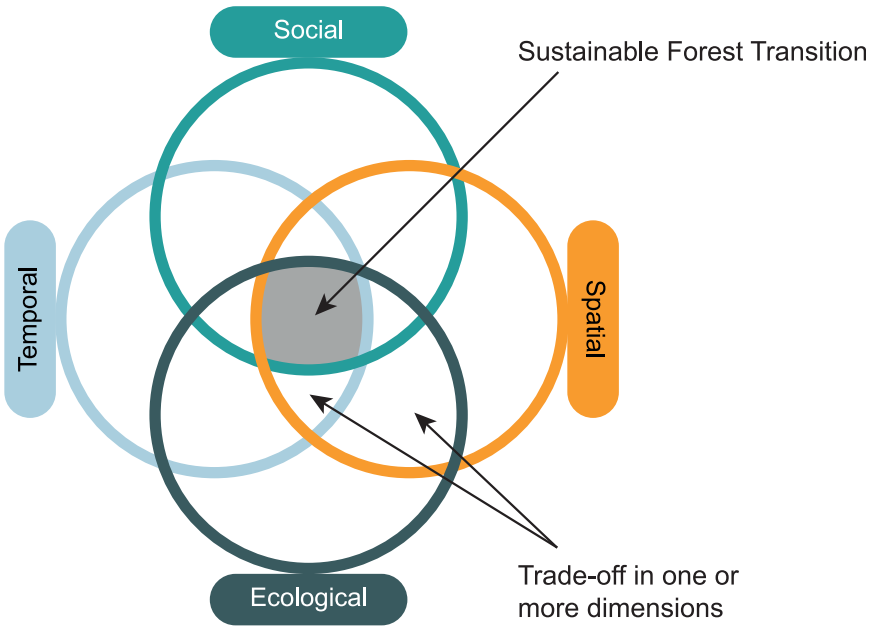

Figure 1. Sustainable forest transition dimensions and potential trade-offs across different dimensions

Our social dimension includes poverty and well-being, livelihoods, equity, and rights to land and resources. Our ecological dimension includes forest gains (natural and planted), biodiversity, and carbon sequestration for climate change mitigation. Our temporal and spatial dimensions consider the temporal and spatial scales over which social and ecological changes occur.

has focused on identifying ecologically effective restoration practices (see, e.g., Erbaugh and Oldekop[20]) and mapping priority areas for biodiversity restoration (see, e.g., Strassburg et al.[21]); (2) land system science, which has explored the complex pathways of land use change and increases in forest cover (see, e.g., Meyfroidt et al.[22]); and (3) environmental social science, which has revealed the interdependencies between people and forests, and analyzed how different policies, institutions, and market forces can support more environmentally effective and socially just forest restoration.[23,24] Each branch of research provides important insights into specific aspects of forest restoration, but in isolation is insufficient to fully understand the system of drivers, conditions, and interactions that influence social-ecological forest dynamics and outcomes.[19]

Despite a growing focus on combining disciplinary perspectives to inform forest restoration (see, e.g., Scheidel and Gingrich and Erbaugh and Oldekop[19,20]), we still lack a comprehensive theory of forest restoration that adequately captures the dynamics and multiple outcomes of forest restoration in varying contexts.[25] Forest transition theory, the one existing conceptual framework for understanding social and policy drivers of forest gain (including both natural forest regeneration and purposeful forest restoration) is insufficient to guide current restoration policy and practice because it does not encompass the social outcomes of drivers of forest gain, nor more nuanced ecological outcomes beyond forest area and biomass stock.[24,25]

To help address this theoretical gap, we introduce a new analytical framework of "sustainable forest transitions" to better understand the ecological and social outcomes (both positive and negative) of reforestation drivers and draw lessons for policy and practice. Implementing our framework will help build empirical evidence that could explain the processes and conditions simultaneously driving lasting improvements in forest cover and social benefits for local populations. We begin by discussing the limitations of existing forest transition theory and how research on forest livelihoods, forest governance, and forest restoration can add important insights to our understanding of the processes, drivers, and joint social and ecological outcomes of forest gains. We then introduce our new analytical framework that incorporates these insights and discuss how advances in the availability and analysis of social and ecological data can be leveraged to operationalize our framework.

FOREST TRANSITION THEORY

Forest transition theory emerged from studies exploring historical land use changes in several high-income countries. These studies proposed that trends in forest cover shift from declines to stable periods of low forest cover to net increases as countries undergo agricultural and forestry intensification and relocation, industrialization, and urbanization.[26,27] Extensions to this work assessed comparable trajectories in low- and middle-income countries and broadly classified drivers into two pathways.[28,29]

The first pathway, often called the economic development pathway,[28] describes forest transitions driven by social, economic, and technological changes in the agricultural, industrial, and service sectors. These changes transform and spatially restructure a country's or region's agricultural production systems, pulling labor away from agriculture in rural areas and toward urban areas (nationally and internationally), while technological advances enable the intensification of agriculture. In turn, these changes make farming on marginal land less profitable, leading to abandonment and regeneration of forests on agriculturally unproductive land.[27] A classic example of this pathway includes the forest transition in Puerto Rico that was driven by industrial transformation on the island in the period after World War II.[30]

The second pathway, often called the forest scarcity pathway,[28] characterizes responses to environmental degradation and declines in the stocks and flows of forest-derived ecosystem services. Forest transitions driven by responses to forest resource scarcity are often the result of actively encouraged reforestation, forest restoration, and afforestation initiatives including tree plantations, on private, collective, and public lands (see, e.g., Hua et al.[31]). These processes are supported by a series of regulatory- and market-based policies and

interventions, including tenure reforms to provide land rights to communities and the establishment of legally protected areas.[32,33] Both pathways often combine and are affected by national and international labor and commodity markets, the development of national and regional policies (e.g., agricultural development programs), infrastructure (e.g., roads) and, more recently, international forest restoration pledges and voluntary biodiversity and carbon offset markets.[34]

STRENGTHS AND WEAKNESSES OF FOREST TRANSITION THEORY

Forest transition theory is the most comprehensive theoretical framework for understanding the drivers of forest gains at global, national, and regional scales. However, the ability of forest transition theory to inform forest restoration agendas in specific socioecological systems is limited because it does not adequately consider the social outcomes of forest transition drivers,[24] ecological outcomes beyond simple measures of forest area or biomass stock, or the spatial and temporal heterogeneity in these outcomes.[25] A more nuanced consideration of social and ecological outcomes would allow forest transition theory to better inform restoration practice.

Forest transitions often result from multiple drivers that interact in space and time and across scales, from the local to the global.[35] For example, Nepal's forest transition resulted from both national forest decentralization policies and international outmigration driven by international labor markets.[32,36] Forest transitions also combine complex dynamics across spatial and temporal scales. Several studies have shown that although a pattern of net forest gain might be apparent at national or regional scales, forest change patterns at more local scales (i.e., within countries or regions) can be highly heterogeneous and characterized by contrasting deforestation and reforestation fronts. These heterogeneous patterns of forest loss and gain have, for example, been shown to characterize forest transitions in parts of Central America[37] and Vietnam.[38] Forest transitions are also not necessarily linear processes, and forest recovery rates can vary over time.[29,39] However, what defines forest transitions in principle is that they are driven by broader structural changes to societies that lead to changes in land use that persist long term.[28,29]

As a land system theory, the forest transition model focuses predominantly on forest area change, neglecting social outcomes and more nuanced ecological outcomes. Although the importance of considering the social impacts of forest transitions was highlighted in historical studies,[40] and there is a developing field of research into the political, livelihood, and equity implications of transition processes,[25,41,42] forest transition theory and most empirical analyses continue to focus primarily on forest area outcomes (see, e.g., Sloan et al.[43]). Failing to consider the social outcomes from forest gain and their drivers could result in policies or interventions that exacerbate social injustices and worsen living conditions for local communities.[5,16,17,41] Furthermore, focusing solely on forest outcomes overlooks the complex interactions and interdependencies between people and forests at the local scale. Such interactions could act to reinforce or reduce forest gains resulting from other drivers (e.g., contrasting migration effects in Nepal[36] and Mexico[44]), meaning that the traditional transition pathways alone may be insufficient to fully understand the processes leading to forest gains in practice.[25] A narrow focus on forest area or even biomass stock neglects other critical forest characteristics, such as forest type (natural or planted), species and genetic diversity, and age, which are key determinants of the benefits that new forests provide to local populations and biodiversity. As such, current forest transition theory insufficiently differentiates transitions driven by the substitution of natural old-growth forest with intensively managed plantations and the potential socio-ecological implications of this theory (although applied research is increasingly doing so[45]). The insufficient consideration of social outcomes and more nuanced forest characteristics is a critical gap, given that the key objectives of the global forest landscape restoration agenda are to improve human well-being, conserve biodiversity, and mitigate climate change.

These limitations, combined with the focus in forest transition theory on historical forest cover, emphasize the need for a more comprehensive and updated theory that explicitly incorporates social and more detailed ecological outcomes. Such a theory is essential to guide research on current restoration challenges and inform practice that is both ecologically effective and socially just. Below, we turn to the body of literature on forests and livelihoods, forest governance, and restoration social science to identify how to incorporate social outcomes and pathways into an analytical framework to support the development of such a theory.

THE IMPORTANCE OF INCORPORATING SOCIAL OUTCOMES INTO FOREST TRANSITION THEORY

Decades of research on forest livelihoods and forest governance as well as the emerging field of restoration social science have revealed the complex interactions and interdependencies between people, forests, and governance institutions. Insights from these fields reveal how and where social outcomes and forest governance fit into forest transition dynamics and the importance of incorporating these factors into theory.

Research on forests' contribution to rural livelihoods has shown the crucial role that forests can play in poverty alleviation by studying how forest's provisioning services (e.g., timber, wood fuel, and non-timber forest products) can support commercial and subsistence livelihoods of rural communities.[4,46] For example, the Centre for International Forestry Research's (CIFOR's) flagship Poverty Environment Network (PEN) study surveyed around 8,000 rural households across 24 low- and middle-income countries. The PEN study found that forest resources account for almost 22% of rural households' income, with a higher share for poorer households.[47] As such, forest transitions and their drivers can significantly affect local people's livelihoods and well-being. These changes, in turn, can alter land-use behaviors in ways that can promote or discourage reforestation.

In parallel, research on forest governance has demonstrated the importance of forest management rights as an important factor influencing both forest change and human well-being. Forest governance, whether community-based, bottom-up (e.g., community forests managed by IPLCs[48]), or state-led, top-down governance (e.g., government-managed protected areas[49]) can affect the benefits that rural communities can gain from

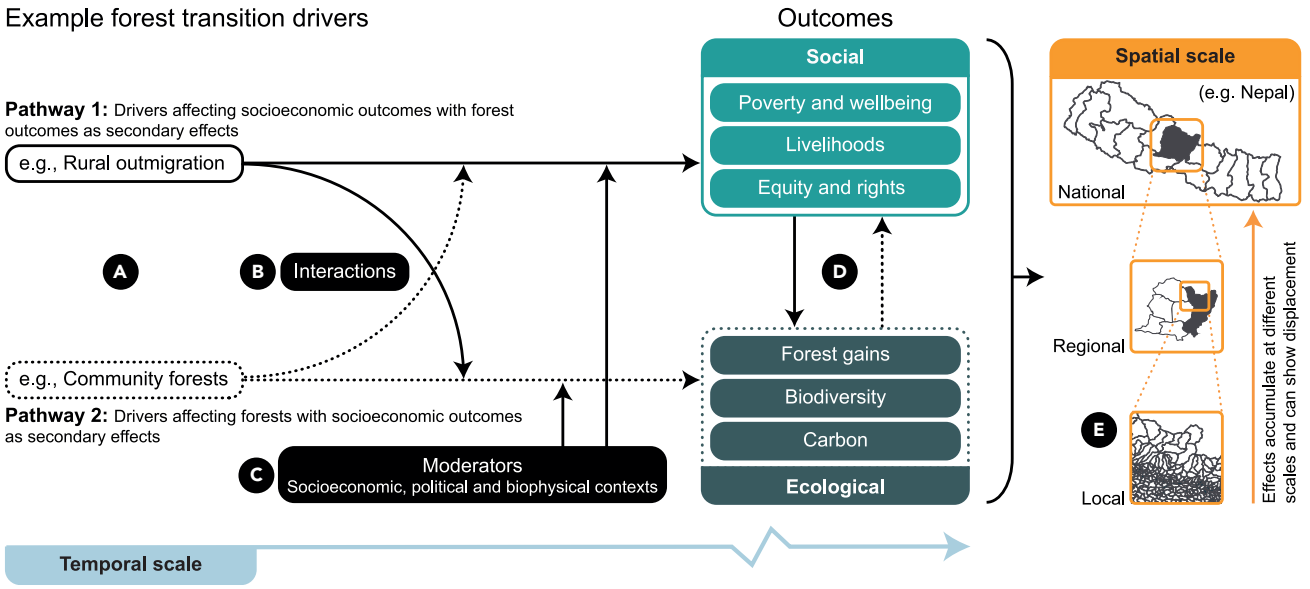

Figure 2. Sustainable forest transition analytical framework linking drivers, contexts, and outcomes at multiple scales and across time
Drivers (A) interact (B) and are moderated (C) by socioeconomic, political and biophysical contexts to affect social and forest ecological outcomes (D) that accumulate at different scales (E).

forests and the direction and extent of forest change. For example, research by the world's largest research program on forest governance, the International Forestry Resources and Institutions (IFRI) network, has used data from almost 800 forests managed by IPLCs in over 20 countries to show that the devolution of forest management rights to IPLCs is often associated with improvements in local livelihoods as well as forest condition.[50,51] Research by IFRI demonstrates that local governance can be an important driver of forest transitions. Meanwhile, national policies and programs moderate the relationship between drivers, forests, and people within these local settings.

Moving beyond a traditional focus on ecological processes and designing ecologically effective restoration interventions, forest restoration research is increasingly considering the social justice and land rights implications of restoration interventions.[16,18,52,53] For example, tree plantations linked to restoration efforts in India have been shown to have had very limited effects on local livelihoods.[54] Research has also shown that certain drivers tend to result in certain types of forest gain. For example, the legal recognition of Indigenous Territories in Brazil has been linked to secondary forest regrowth that has distinct potential social and ecological outcomes.[55] This understanding adds nuance to forest transition theory and helps practitioners to identify restoration interventions that are more likely to be socially just and deliver the multiple objectives of the global forest restoration agenda.

The above work on forest livelihoods and forest governance has been critical in developing our understanding of the interactions between forests, people, governance institutions, and the social impacts of restoration interventions. However, much of this evidence comes from local case studies or cross-sectional studies, such as CIFOR's PEN study and IFRI's research program, which limits the scope for understanding long-term changes and dynamics at scale.[56] Furthermore, the restoration literature has seldom considered socio-ecological dynamics beyond the focal areas of interest, such as teleconnections, displaced impacts, or effects across scales (see, e.g., Wiegant et al.[57]). The greater availability of high-resolution, longitudinal environmental and social data (described below), coupled with improved computing power and novel methods of analysis, enable the expansion of this work across broad spatial and temporal scales and its incorporation in a more comprehensive framework of forest transitions.

A NEW FRAMEWORK TO UNDERSTAND AND STUDY SUSTAINABLE FOREST TRANSITIONS

Our sustainable forest transitions framework significantly extends the current forest transition theory and its relevance to current restoration challenges by incorporating social outcomes and more nuanced ecological outcomes. Our framework also incorporates direct and indirect drivers of forest gain, relative effects that vary over space, interactions between drivers, and the moderating influence of social, political, and biophysical contexts. Our framework organizes drivers, outcomes, and contexts into a multi-tier system operating across spatial scales and time (Figure 2) and explicitly promotes consideration of the four key dimensions highlighted as being critical for successful forest restoration in international agendas (Figure 1).

Our framework groups outcomes into the broad categories of social and forest ecological outcomes. Social outcomes incorporate the specific dimensions of poverty and well-being, livelihoods, equity, and land and resource rights. Forest ecological outcomes include forest area gains (natural and planted), biodiversity, and climate change mitigation through carbon storage. We selected these dimensions as they are central goals of the global forest restoration agenda.[5,16–18,53] Although researchers may not have access to data to assess all these dimensions,

we hope the framework encourages a more nuanced analysis of outcomes of forest transitions drivers, beyond the traditional focus on forest area. In addition, researchers may choose to add other outcomes of interest (e.g., food security, climate resilience) if data are available.

Our framework includes the drivers linked to economic development and resource scarcity conceptualized in the original forest transition model but re-organizes drivers into two new pathways (Figure 2A). We refer to pathways as a distinct set of drivers that produce a distinct sequence of outcomes. Pathway 1 corresponds to drivers that principally affect social outcomes with forest ecological outcomes as a secondary effect. For example, outmigration can affect rural livelihoods and land use, with reforestation resulting as an indirect effect from agricultural abandonment. Pathway 2 captures drivers that principally target forest ecological outcomes, with social outcomes resulting as secondary effects. Many drivers in pathway 2 include initiatives that can positively or negatively affect community rights to forests and resources, which can have significant impacts on social outcomes (e.g., by facilitating or restricting the use and sale of forest products for subsistence and commercial purposes). Rights to land and forest resources in our framework can therefore be considered both distinct outcomes (e.g., outcomes driven by specific policies such as tenure reforms[48]) and as drivers of change (e.g., in the case of community forests[32]).

Our framework explicitly acknowledges key interactions: the two pathways do not act in isolation but interact with each other (Figure 2B) and moderate context-specific social, political, and biophysical factors. Such interactions can amplify or weaken the effect of different drivers and produce spatial heterogeneity in outcomes (Figure 2C). The importance of context is illustrated, for example, by the contrasting effects of cash transfers and rural credit programs on deforestation in different regions of Brazil.[58]

Finally, our framework considers both temporal and spatial scales, which can now be better understood thanks to advances in the availability of longitudinal and high spatial resolution data (see below). Spatial variation in the outcomes of forest transition drivers can influence how outcomes accumulate and manifest at larger scales. For instance, community forestry may be effective at improving both forest cover and human well-being in places that have strong institutions and lower levels of poverty (see, e.g., Oldekop et al.[32]), but this positive effect may only be apparent at the local scale and may be averaged out when measuring outcomes at broad scales (e.g., at the scale of provinces or countries). Similarly, displacement of deforestation may only become apparent when considering patterns of forest gains and losses over broad spatial scales (see, e.g., Meyfroidt et al.[38]). For this reason, our framework explicitly calls for combining research at multiple spatial scales (e.g., local, regional, or national) to explore how outcomes and the relative importance of different drivers vary across scales (Figure 2E).

OPERATIONALIZING THE ANALYTICAL FRAMEWORK

To our knowledge, no single study of forest transitions has yet integrated all components of our framework. Therefore, to illustrate how our framework could be applied in practice to unify these different components, we present a hypothetical example from Nepal. To inform our hypothetical case study we draw on evidence from case studies, from Nepal and elsewhere, on the individual effect of migration[32] and community forests[36] on forest cover and poverty.

In a first step (Figure 2A), we identify key forest transition drivers and categorize them into the two pathways. In Nepal, key drivers associated with the country's forest transition include high international outmigration rates that have transformed rural landscapes (according to the 2010 census, one in three households had someone working abroad[36]) and the large and long-standing community forest management program (~25% of Nepal's forests are managed by local communities[32]). International migration will likely affect forest cover changes through changes in socioeconomic well-being outcomes (e.g., remittances) that affect agricultural decisions (pathway 1). Community forests are principally targeted toward forest conservation and restoration and likely impact socioeconomic well-being through subsistence and commercial livelihood benefits (pathway 2).

In a second step (Figure 2B), we consider whether and how these drivers interact when operating simultaneously. For example, outmigration has been linked to lower levels of community engagement in local forest management institutions in Mexico.[59] Outmigration in Nepal might, therefore, interact similarly with community forest management institutions and influence the effect of community forest management on forests and social outcomes. We should also consider how context-specific social, political, and biophysical factors might moderate the effects of a particular driver (e.g., outmigration) on both social and forest ecological outcomes (Figure 2C). Contextual factors operating across a range of scales may be important drivers of heterogeneity and should be considered; these could range from macroeconomic trade policies or subsidies that influence local land use and labor, to micro-scale biophysical factors, such as slope and soil quality.[60] In Nepal, for example, where much of the agricultural production takes place on steep hillsides, slope is a key moderator of outmigration's effect on forest gains.[36]

In a third step (Figure 2D), we assess the mechanisms through which indirect effects occur—how social changes resulting from drivers in pathway 1 affect forests. In Nepal, the effect of outmigration on forests is mediated through changes in population density and agricultural activity.[36] Finally, it is important to consider scale-dependent effects (Figure 2E). Both community forests and international outmigration are widespread in Nepal but are also spatially determined; migration is particularly high in central and western Nepal,[36] whereas community forest management is particularly prominent across the middle hills range of the country.[32] Whether international migration or community forests lead to the largest amounts of forest gain at national scales, or whether outcomes vary depending at what scale data are aggregated remains to be explored.

Our framework can be used to ask both reverse causal questions (what explains outcome Y?) and forward causal questions (does driver X cause outcome Y?)[61] and can also be informed by qualitative data and qualitative causal approaches.[62] Reverse causal questions are important for exploratory analyses, hypothesis generation, and theory development. In contrast, forward causal questions are important for hypothesis testing and attributing causation, often in the context of policy evaluation.

Reverse causal questions can be answered using a series of regression models. The patterns and drivers of observed forest gains can be identified by regressing forest gain and social outcomes against predictors, including suspected drivers, interactions between them, and potentially important contextual factors.

Quasi-experimental approaches, which use statistical methods to simulate randomized controlled trials using observational data, can be applied to answer forward causal questions. Over the past 15 years, these methods have been increasingly applied to evaluate the impacts of environmental policies[63,64] but have seldom been used to analyze forest gains, compared to efforts to estimate forest loss (but see Andam et al.,[33] Oldekop et al.,[36] Benzeev et al.,[55] and Baragwanath et al.[65]). For example, statistical matching – a statistical pre-processing step to select more comparable units of analysis, has been used to assess deforestation and poverty outcomes of protected areas and community forests in different country-level analyses (e.g., Oldekop et al.[32] and Ferraro et al.[66]). Other quasi-experimental methods, such as regression discontinuity analyses, which use thresholds in time series data to define treatment assignment, and the synthetic control, which uses a weighted combination of control units for analyses where the pool of potential controls is limited (e.g., West et al.[67]), are also becoming more prevalent.

A key advantage of quasi-experimental methods in the context of our framework is that they can be used to understand relative effects (which one of the multiple drivers operating at the same time and place has the largest effect) and extended to better understand the contextual factors that moderate or mediate outcomes.[66,68] Moderators affect the causal relationship between drivers and outcomes. Understanding them is essential to understanding how the same drivers can yield different effects, and interact differently, in different places (see points B and C in Figure 2). For example, access to roads and agricultural suitability have been shown to moderate the impact of protected areas on deforestation and poverty alleviation in contrasting ways.[66] Mediators explain the mechanism through which drivers affect outcomes (Figure 2D). In the context of our framework, analyzing mediators can help understand the indirect forest or social outcomes of different drivers.

ADVANCES IN THE AVAILABILITY OF FOREST AND SOCIAL DATA

Applying our framework to better understand the social and ecological outcomes of forest transitions requires the analysis of high-resolution data on the social and ecological characteristics of the study region across multiple time periods. In recent years, two key advances facilitate the study of forest transitions. The first is improvements in remote sensing capacity and the availability of secondary data products that enable researchers to capture forest changes more accurately and more frequently at regional (see, e.g., Vancutsem et al.,[69] Sousa Jr. et al.[70]) and global scales.[71] The second is data products that allow researchers to distinguish between different types of forest gains, including plantations and tree crops,[72–75] although recent, consistent, and comprehensive global data on plantation extent are still lacking.[76]

Datasets used to measure poverty and well-being, typically used in development economics, are being used increasingly to study the social outcomes of environmental policies. For example, census data and representative household surveys (e.g., the World Bank's Living Standards Measurement Study, and the US Agency for International Development's [USAID] Demographic and Health Survey [DHS; note that with the restructuring of USAID implemented by the second Trump administration, the DHS program has been put on hold]) are available for multiple time periods in many countries and can be used to construct panels or pseudo-panels to measure poverty and well-being changes over time.[77] As such, these data can be used to evaluate the effects of forest transition drivers on human well-being (see, e.g., den Braber et al.[78] for an example using deforestation outcomes).

In the last 5 years, we have also seen the release of high-resolution gridded poverty and well-being datasets that facilitate analyses in previously data-poor areas. For example, Chi et al.[79] and Sherman et al.[80] have used machine learning algorithms to relate representative household survey data to population estimates and characteristics from satellite imagery (e.g., nightlights), to predict wealth and economic development at relatively high spatial resolutions (e.g., 2.4 km^2) for much of the world. A key advantage of gridded social data is that it can be easily aggregated to match the unit of analysis (e.g., Figure 3), the scale of an intervention of interest, or to align with lower-resolution datasets. However, most of these datasets do not currently measure changes over time (but see Kummu et al.[81]) and are themselves models, which presents some analytical difficulties.

New social datasets have also been released that capture, or proxy, potential drivers of forest transitions, and important socioeconomic and political contexts. These include high-resolution, gridded data on areas managed by Indigenous people[83] (Figure 3), net migration[82] (Figure 3), and agricultural gross domestic product.[84] This adds to the existing data on population (e.g., WorldPop), accessibility (e.g., travel times to urban centers[85]), and forest governance data (e.g., protected areas[86]). By integrating these new gridded social and governance data with forest cover change and other biophysical data, scholars can simultaneously (1) incorporate multiple drivers of deforestation and/or reforestation beyond forest sector policies and (2) evaluate forest transitions across different spatial scales over a long period of time. It is important to note, however, that many broad-scale social datasets have limitations and uncertainties, and it is important to recognize these when selecting datasets and interpreting analyses.

Some critical data also remain missing or difficult to access. Consistent data on the composition and biodiversity of forest species continue to be a challenge. However, citizen science-based efforts, such as eBird can be used to assess biodiversity outcomes of certain species over large geographical scales (see, e.g., Cazalis et al.[87]). The absence of systematic and accessible data on forest restoration projects and Payments for Ecosystem Services schemes in many countries constitutes a serious gap, preventing independent assessments of the social and environmental impacts of restoration projects and interventions. This is particularly concerning given that such projects are often linked to carbon and biodiversity offset markets that have been

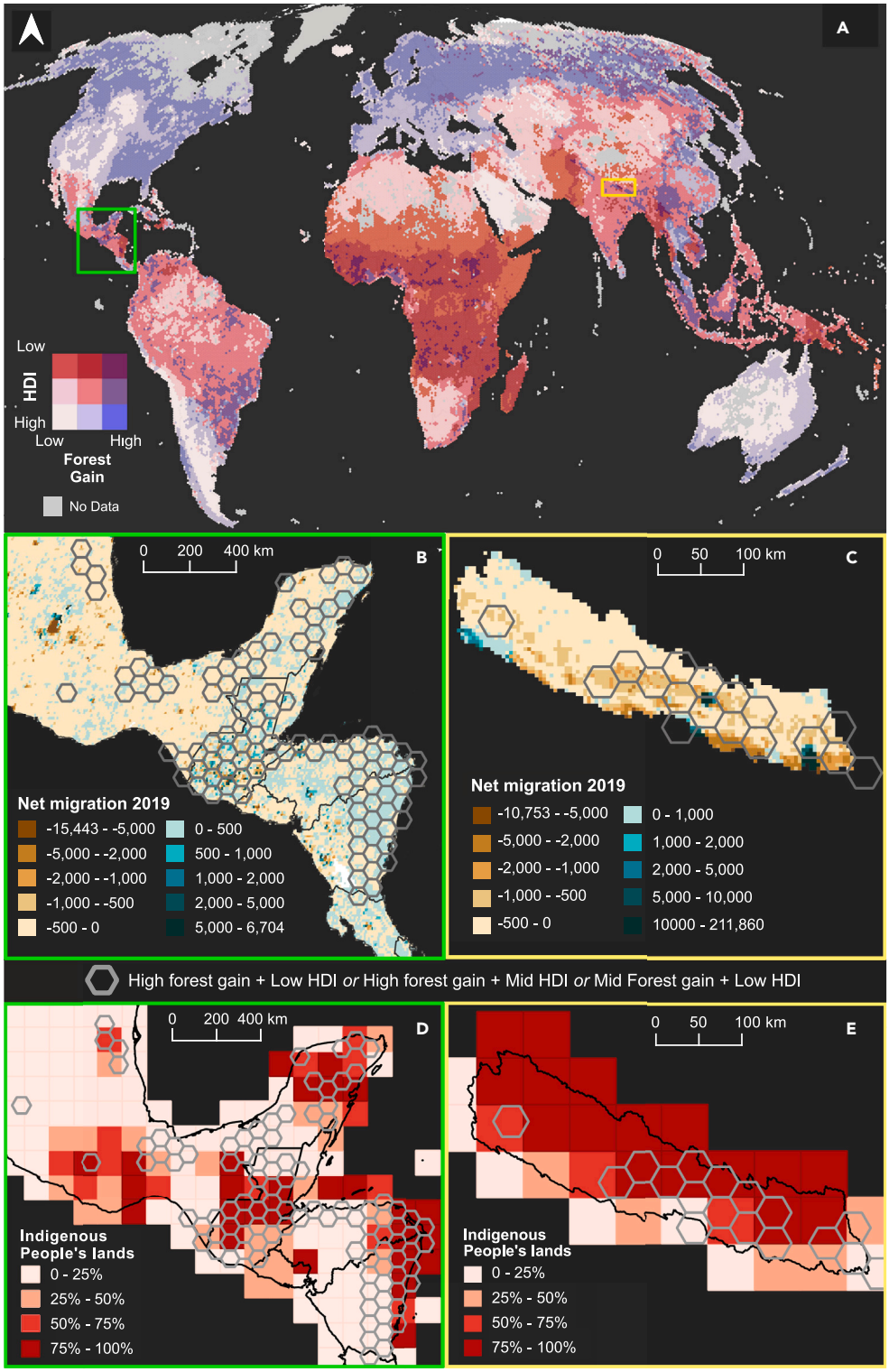

Figure 3. Combining new global datasets within the sustainable forest transitions framework enables broad-scale evaluations of the multiple drivers and outcomes of reforestation

(A) Forest and poverty outcomes are mapped at the global scale, combining new, tree height-based estimates of forest gain from 2000 to 2020,[62] with high-resolution estimates of the Human Development Index (HDI) for 2019,[80] summarized within a 3,700-km^2 hex grid. This highlights where tree cover is expanding in places with low to mid-human development (<0.7), where the need for sustainable forest transitions is particularly pronounced.

(B–E) The focus here is on two places, mid-Central America (B and D) and Nepal (C and E), which demonstrates how new social datasets, in this case migration[82] (B and C) and Indigenous Territories[83] (D and E), can be used to assess the relative effects of suspected drivers on both forest cover and poverty.

insufficiently evaluated and, in some cases, criticized for generating adverse social and/or environmental outcomes.[67]

CONCLUSION

In this paper, we advance a new framework to understand the social and ecological outcomes of forest gain drivers. Our framework significantly extends the current forest transition theory, integrating insights from research on forest livelihoods, governance, and restoration to incorporate social outcomes and ecological outcomes beyond forest area gain, and paying much greater attention to interactions between forest gain drivers and the social and political contexts in which they operate. Advances in data availability and methodological tools enable the application of our framework to analyze the drivers and outcomes of forest gains across temporal and spatial scales.

The empirical application of our framework could improve the understanding of (1) how synergies and trade-offs between social and ecological outcomes are distributed across time and space; (2) which current forest gain drivers, including key national and global environmental policies, lead to joint positive social and ecological outcomes (i.e., synergies); and (3) how different social and political contexts act to amplify or weaken forest gain drivers or moderate their well-being outcomes. This understanding would provide evidence on the processes and conditions under which increasing forest cover can also deliver social benefits for local populations. Empirical evidence generated from application of our framework could help improve the design and targeting of forest restoration interventions to increase their efficiency as well as the odds that they deliver the promised benefits for people, climate, and biodiversity, at scales envisioned by ambitious global targets.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Johan A. Oldekop (johan.oldekop@manchester.ac.uk).

Materials availability

This study did not generate new unique materials.

Data and code availability

Except for data on Indigenous territories, all data used to generate Figure 3 are in the public domain and can be downloaded from the references provided. The data on Indigenous territories were kindly made available to us by Garnett et al.[83]

ACKNOWLEDGMENTS

J.A.O., K.D., L.A., M.H.-M., and S.N. were funded by a UK Research and Innovation Frontier Research Grant (EP/X023222/1), which was selected by the European Research Council. R.P. and J.A.O. acknowledge funding from the Economic and Social Research Council (ES/Y002660/1). S.J. was supported by a Humboldt International Climate Protection Postdoctoral Fellowship. D.K.T. was supported by a British Academy Visiting Fellowship (no. VF2\100601). We thank Forrest Fleischman for helpful comments on an initial draft of this manuscript and are grateful to three reviewers for their constructive review of our submitted manuscript.

AUTHOR CONTRIBUTIONS

J.A.O., K.D., L.A., J.T.E., M.H.-M., S.J., S.N., and R.P. wrote a first draft of the framework and paper. All authors contributed to subsequent refinements of the framework and paper.

DECLARATION OF INTERESTS

J.A.O. is a member of the Methods Expert Group of the EKLIPSE science policy initiative and is also a member of the Expert Advisory Group of the UK Department for Environment, Food & Rural Affairs Global Center on Biodiversity for Climate. P.M. is a member of the piloting group Evaluation and Scaling up of Nature-Based Solutions of PEPR Solu-BioD (CNRS and INRAE, France) and a member of the Scientific Advisory Committee of the Trase initiative (www.trase.earth). This work contributes to the Global Land Program (https://glp.earth).

REFERENCES

1. Bastin, J.-F., Finegold, Y., Garcia, C., Mollicone, D., Rezende, M., Routh, D., Zohner, C.M., and Crowther, T.W. (2019). The global tree restoration potential. Science *365*, 76–79. https://doi.org/10.1126/science.aax0848.
2. Lewis, S.L., Wheeler, C.E., Mitchard, E.T.A., and Koch, A. (2019). Restoring natural forests is the best way to remove atmospheric carbon. Nature *568*, 25–28. https://doi.org/10.1038/d41586-019-01026-8.
3. Reyes-García, V. (2019). The contribution of Indigenous Peoples and local communities to ecological restoration. Restor. Ecol. *27*, 3–8. https://doi.org/10.1111/rec.12894.
4. Miller, D.C., and Hajjar, R. (2020). Forests as pathways to prosperity: Empirical insights and conceptual advances. World Dev. *125*, 104647. https://doi.org/10.1016/j.worlddev.2019.104647.
5. Elias, M., Kandel, M., Mansourian, S., Meinzen-Dick, R., Crossland, M., Joshi, D., Kariuki, J., Lee, L.C., McElwee, P., Sen, A., et al. (2022). Ten people-centred rules for socially sustainable ecosystem restoration. Restor. Ecol. *30*, e13574. https://doi.org/10.1111/rec.13574.
6. United Nations General Assembly (2015). Transforming Our World: The 2030 Agenda for Sustainable Development. A/RES/70/1.
7. United Nations (UN) (2015). Paris Agreement.
8. United Nations Environment Programme (UNEP) (2011). The Bonn Challenge (2011)
9. United Nations Climate Summit (2014). New York Declaration on Forests.
10. United Nations General Assembly (2019). United Nations Decade on Ecosystem Restoration (2021-2030). A/RES/73/284.
11. United Nations Environment Programme (2022). Convention on Biological Diversity. CBD/COP/DEC15/4.
12. United Nations Climate Change Conference (2021). Glasgow Leader's Declaration on Forests and Land Use.
13. United Nations Climate Change Conference (2021). The Global Forest Finance Pledge.
14. Stanturf, J.A., and Mansourian, S. (2020). Forest landscape restoration: state of play. R. Soc. Open Sci. *7*, 201218. https://doi.org/10.1098/rsos.201218.
15. Mansourian, S. (2018). In the eye of the beholder: Reconciling interpretation of Forest Landscape Restoration. Land Degrad. Dev. *29*, 2888–2898. https://doi.org/10.1002/ldr.3014.
16. Di Sacco, A., Hardwick, K.A., Blakesley, D., Brancalion, P.H.S., Breman, E., Cecilio Rebola, L., Chomba, S., Dixon, K., Elliott, S., Ruyonga, G., et al. (2021). Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery, and livelihood benefits. Glob. Chang. Biol. *27*, 1328–1348. https://doi.org/10.1111/gcb.15498.
17. Food and Agriculture Organisation of the United Nations (FAO); International Union for Conservation of Nature's Commission on Ecosystem Restoration (IUCN CEM); Society for Ecological Restoration (SER) (2021). Principles for Ecosystem Restoration to Guide the United Nations Decade 2021-2030 (FAO).
18. Löfqvist, S., Kleinschroth, F., Bey, A., de Bremond, A., DeFries, R., Dong, J., Fleischman, F., Lele, S., Martin, D.A., Messerli, P., et al. (2023). How social considerations improve the equity and effectiveness of ecosystem restoration. Bioscience *73*, 134–148. https://doi.org/10.1093/biosci/biac099.
19. Scheidel, A., and Gingrich, S. (2020). Toward sustainable and just forest recovery: research gaps and potentials for knowledge integration. One Earth *3*, 680–690. https://doi.org/10.1016/j.oneear.2020.11.005.

20. Erbaugh, J.T., and Oldekop, J.A. (2018). Forest landscape restoration for livelihoods and well-being. Curr. Opin. Environ. Sustain. *32*, 76–83. https://doi.org/10.1016/j.cosust.2018.05.007.

21. Strassburg, B.B.N., Iribarrem, A., Beyer, H.L., Cordeiro, C.L., Crouzeilles, R., Jakovac, C.C., Braga Junqueira, A., Lacerda, E., Latawiec, A.E., Balmford, A., et al. (2020). Global priority areas for ecosystem restoration. Nature *586*, 724–729. https://doi.org/10.1038/s41586-020-2784-9.

22. Meyfroidt, P., Roy Chowdhury, R., de Bremond, A., Ellis, E.C., Erb, K.-H., Filatova, T., Garrett, R.D., Grove, J.M., Heinimann, A., Kuemmerle, T., et al. (2018). Middle-range theories of land system change. Glob. Environ. Change *53*, 52–67. https://doi.org/10.1016/j.gloenvcha.2018.08.006.

23. Erbaugh, J.T., Pradhan, N., Adams, J., Oldekop, J.A., Agrawal, A., Brockington, D., Pritchard, R., and Chhatre, A. (2020). Global forest restoration and the importance of prioritizing local communities. Nat. Ecol. Evol. *4*, 1472–1476. https://doi.org/10.1038/s41559-020-01282-2.

24. Kull, C.A., Bartmess, J., Dressler, W., Gingrich, S., Grodzicki, M., Jasikowska, K., Lapniewska, Z., Manourian, S., Nguyen, V.T.H., Persson, J., et al. (2024). Pitfall for the sustainability of forest transitions: evidence from Southeast Asia. Environ. Conserv. *23*, 1–11. https://doi.org/10.1017/S0376892924000079.

25. Persson, J. (2024). On the brink of transition. From pathways to methodological heuristics for improved causal analysis of forest transition research. Land Use Policy *147*, 107376. https://doi.org/10.1016/j.landusepol.2024.107376.

26. Mather, A.S. (1992). The forest transition. Area *24*, 367–379. https://www.jstor.org/stable/20003181.

27. Mather, A.S., and Needle, C.L. (1998). The forest transition: a theoretical approach. Area *30*, 117–124. https://www.jstor.org/stable/20003865.

28. Rudel, T.K., Coomes, O.T., Moran, E., Achard, F., Angelsen, A., Xu, J., and Lambin, E. (2005). Forest transitions: towards a global understanding of land use change. Glob. Environ. Change *15*, 23–31. https://doi.org/10.1016/j.gloenvcha.2004.11.001.

29. Meyfroidt, P., and Lambin, E.F. (2011). Global forest transition: prospects for an end to deforestation. Annu. Rev. Environ. Resour. *36*, 343–371. https://doi.org/10.1146/annurev-environ-090710-143732.

30. Rudel, T.K., Perez-Lugo, M., and Zichal, H. (2000). When fields revert to forest: Development and spontaneous reforestation in post-war Costa Rica. Prof. Geogr. *53*, 386–397. https://doi.org/10.1111/0033-0124.00233.

31. Hua, F., Wang, X., Zheng, X., Fisher, B., Wang, L., Zhu, J., Tang, Y., Yu, D.W., and Wilcove, D.S. (2016). Opportunities for biodiversity gains under the world's largest reforestation programme. Nat. Commun. *7*, 12717. https://doi.org/10.1038/ncomms12717.

32. Oldekop, J.A., Sims, K.R.E., Karna, B.K., Whittingham, M.J., and Agrawal, A. (2019). Reductions in deforestation and poverty from decentralized forest management in Nepal. Nat. Sustain. *2*, 421–428. https://doi.org/10.1038/s41893-019-0277-3.

33. Andam, K.S., Ferraro, P.J., and Hanauer, M.M. (2013). The effects of protected areas on ecosystem restoration: a quasi-experimental design to estimate the impact of Costa Rica's protected area system on forest regrowth. Conserv. Lett. *6*, 317–323. https://doi.org/10.1111/conl.12004.

34. Andres, S.E., Standish, R.J., Lieurance, P.E., Mills, C.H., Harper, R.J., Butler, D.W., Adams, V.M., Lehmann, C., Tetu, S.G., Cuneo, P., et al. (2022). Defining biodiverse reforestation: Why it matters for climate change mitigation and biodiversity. Plants, People, Planet *5*, 27–38. https://doi.org/10.1002/ppp3.10329.

35. Gingrich, S., Lauk, C., Krausmann, F., Erb, K.-H., and Le Noë, J. (2021). Changes in energy and livestock systems largely explain the forest transition in Austria (1830-1910). Land Use Policy *109*, 105624. https://doi.org/10.1016/j.landusepol.2021.105624.

36. Oldekop, J.A., Sims, K.R.E., Whittingham, M.J., and Agrawal, A. (2018). An upside to globalization: International migration drives reforestation in Nepal. Glob. Environ. Change *52*, 66–74. https://doi.org/10.1016/j.gloenvcha.2018.06.004.

37. Redo, D.J., Grau, H.R., Aide, T.M., and Clark, M.L. (2012). Asymmetric forest transition driven by the interaction of socioeconomic development and environmental heterogeneity in Central America. Proc. Natl. Sci. Acad. USA *109*, 8839–8844. https://doi.org/10.1073/pnas.1201664109.

38. Meyfroidt, P., Vu, T.P., and Hoang, V.A. (2013). Trajectories of deforestation, coffee expansion and displacement of shifting cultivation in the Central Highlands of Vietnam. Glob. Environ. Change *23*, 1187–1198. https://doi.org/10.1016/j.gloenvcha.2013.04.005.

39. Sloan, S. (2022). Reforestation reversals and forest transitions. Land Use Policy *112*, 105800. https://doi.org/10.1016/j.landusepol.2021.105800.

40. Mather, A.S., Fairbairn, J., and Needle, C.L. (1999). The course and drivers of the forest transition: The case of France. J. Rural Stud. *15*, 65–90. https://doi.org/10.1016/S0743-0167(98)00023-0.

41. Pichler, M., Bhan, M., and Gingrich, S. (2021). The social and ecological costs of reforestation. Territorialization and industrialization of land use accompany forest transitions in Southeast Asia. Land Use Policy *101*, 105180. https://doi.org/10.1016/j.landusepol.2020.105180.

42. Kull, C.A. (2017). Forest transitions: a new conceptual scheme. Geogr. Helv. *72*, 465–474. https://doi.org/10.5194/gh-72-465-2017.

43. Sloan, S., Meyfroidt, P., Rudel, T.K., Bongers, F., and Chazdon, R. (2019). The forest transformation: Planted tree cover and regional dynamics of tree gains and losses. Glob. Environ. Change *59*, 101988. https://doi.org/10.1016/j.gloenvcha.2019.101988.

44. García-Barrios, L., Galván-Miyoshi, Y.M., Valsieso-Pérez, I.A., Masera, O.R., Bocco, G., and Vandermeer, J. (2009). Neotropical forest conservation, agricultural intensification, and rural out-migration: The Mexican experience. Bioscience *59*, 863–873. https://doi.org/10.1525/bio.2009.59.10.8.

45. Heilmayr, R., Echeverría, C., Fuentes, R., and Lambin, E.F. (2016). A plantation-dominated forest transition in Chile. Appl. Geogr. *75*, 71–82. https://doi.org/10.1016/j.apgeog.2016.07.014.

46. D.C. Miller, S. Mansourian, and S. Wildburger, eds. (2020). Forest, trees and the eradication of poverty: Potential and limitations (IUFRO).

47. Angelsen, A., Jagger, P., Babigumira, R., Belcher, B., Hogarth, N.J., Bauch, S., Börner, J., Smith-Hall, C., and Wunder, S. (2014). Environmental incomes and rural livelihoods: A global-comparative analysis. World Dev. *64*, S12–S28. https://doi.org/10.1016/j.worlddev.2014.03.006.

48. Hajjar, R., Oldekop, J.A., Cronkleton, P., Newton, P., Russell, A.J.M., and Zhou, W. (2020). A global analysis of the social and environmental outcomes of community forests. Nat. Sustain. *4*, 216–224. https://doi.org/10.1038/s41893-020-00633-y.

49. Oldekop, J.A., Holmes, G., Harris, W.E., and Evans, K.L. (2016). A global analysis of the social and conservation outcomes of protected areas. Conserv. Biol. *30*, 133–141. https://doi.org/10.1111/cobi.12568.

50. Persha, L., Agrawal, A., and Chhatre, A. (2011). Social and ecological synergy: Local rulemaking, forest livelihoods, and biodiversity conservation. Science *331*, 1606–1608. https://doi.org/10.1126/science.1199343.

51. Fischer, H.W., Chhatre, A., Duddu, A., Pradhan, N., and Agrawal, A. (2023). Community forest governance and synergies among carbon, biodiversity and livelihoods. Nat. Clim. Chang. *13*, 1340–1347. https://doi.org/10.1038/s41558-023-01863-6.

52. McLain, R., Lawry, S., Guariguata, M.R., and Reed, J. (2021). Toward a tenure-responsive approach to forest landscape restoration: A proposed tenure diagnostic for assessing restoration opportunities. Land Use Policy *104*, 103748. https://doi.org/10.1016/j.landusepol.2018.11.053.

53. Osborne, T., Brock, S., Chazdon, R., Chomba, S., Garen, E., Gutierrez, V., Lave, R., Lefevre, M., and Sundberg, J. (2021). The political ecology playbook for ecosystem restoration: Principles for effective, equitable, and transformative landscapes. Glob. Environ. Change *70*, 102320. https://doi.org/10.1016/j.gloenvcha.2021.102320.

54. Coleman, E.A., Schultz, B., Ramprasad, V., Fischer, H., Rana, P., Filippi, A.M., Güneralp, B., Ma, A., Rodriguez Solorzano, C., Guleria, V., et al. (2021). Limited effects of tree planting on forest cover and rural livelihoods in Northern India. Nat. Sustain. *4*, 997–1004. https://doi.org/10.1038/s41893-021-00761-z.

55. Benzeev, R., Zhang, S., Rauber, M.A., Vance, E.A., and Newton, P. (2023). Formalizing land tenure of Indigenous lands improved forest outcomes in the Atlantic Forest of Brazil. PNAS Nexus *2*, pgac287. https://doi.org/10.1093/pnasnexus/pgac287.

56. Jagger, P., Cheek, J.Z., Miller, D., Ryan, C., Shyamsundar, P., and Sills, E. (2022). The role of forests and trees in poverty dynamics. For. Policy Econ. *140*, 102750. https://doi.org/10.1016/j.forpol.2022.102750.

57. Wiegant, D., Peralvo, M., van Oel, P., and Dewulf, A. (2020). Five scale challenges in Ecuadorian forest and landscape restoration governance. Land Use Policy *96*, 104686. https://doi.org/10.1016/j.landusepol.2020.104686.

58. Dyngeland, C., Oldekop, J.A., and Evans, K.L. (2020). Assessing multidimensional sustainability: Lessons from Brazil's social protection programs. Proc. Natl. Sci. Acad. USA *117*, 20511–20519. https://doi.org/10.1073/pnas.1920998117.

59. Robson, J., and Berkes, F. (2011). How does out-migration affect community institutions? A study of two indigenous municipalities in Oaxaca, Mexico. Hum. Ecol. *39*, 179–190. https://doi.org/10.1007/s10745-010-9371-x.

60. Oldekop, J.A., Gabay, M., Humphreys, D., Kamoto, J.F.M., Mutta, D.N., Song, C., Timko, J., Rasmussen, L.V., and Stoian, D. (2021). A framework for analysing contextual factors shaping forest-poverty dynamics. For. Policy Econ *132*, 102591. https://doi.org/10.1016/j.forpol.2021.102591.

61. Gelman, A., and Imbens, G. (2013). Why ask why? Forward causal inference and reverse causal questions. NBER Working Paper Series 19614. https://doi.org/10.3386/w19614

62. Zavaleta Cheek, J., Eklund, J., Merten, N., Brooks, J., and Miller, D.C. (2023). A guide to qualitative attribution models for evaluation in conservation. Conserv. Biol. *37*, e14071. https://doi.org/10.1111/cobi.14071.

63. Baylis, K., Honey-Rosés, J., Börner, J., Corbera, E., Ezzine-de-Blas, D., Ferraro, P.J., Lapeyre, R., Persson, U.M., Pfaff, A., and Wunder, S. (2016). Mainstreaming impact evaluation in nature conservation. Conserv. Lett. *9*, 58–64. https://doi.org/10.1111/conl.1218.

64. Schleicher, J., Eklund, J., D Barnes, M., Geldmann, J., Oldekop, J.A., and Jones, J.P.G. (2020). Statistical matching for conservation science. Conserv. Biol. *34*, 538–549. https://doi.org/10.1111/cobi.13448.

65. Baragwanath, K., Bayi, E., and Shinde, N. (2023). Collective property rights lead to secondary forest growth in the Brazilian Amazon. Proc. Natl. Sci. Acad. USA *120*, e2221346120. https://doi.org/10.1073/pnas.2221346120.

66. Ferraro, P.J., Hanauer, M.M., and Sims, K.R.E. (2011). Conditions associated with protected area success in conservation and poverty reduction. Proc. Natl. Sci. Acad. USA *108*, 13913–13918. https://doi.org/10.1073/pnas.1011529108.

67. West, T.A.P., Wunder, S., Sills, E.O., Börner, J., Rifai, S.W., Neidermeier, A.N., Frey, G.P., and Kontoleon, A. (2023). Action needed to make carbon offsets from forest conservation work climate change mitigation. Science *381*, 873–877. https://doi.org/10.1126/science.ade3535.

68. Ferraro, P.J., and Hanauer, M.M. (2014). Quantifying causal mechanisms to determine how protected areas affect poverty through changes in ecosystem services and infrastructure. Proc. Natl. Sci. Acad. USA *111*, 4332–4337. https://doi.org/10.1073/pnas.1307712111.

69. Vancutsem, C., Achard, F., Pekel, J.-F., Vieilledent, G., Carboni, S., Simonetti, D., Gallego, J., Aragão, L.E.O.C., and Nasi, R. (2021). Long-term (1990-2019) monitoring of forest cover change in the humid tropics. Sci. Adv. *7*, eabe1603. https://doi.org/10.1126/sciadv.abe1603.

70. Souza, C.M., Jr., Shimbo, J.Z., Rosa, M.R., Parente, L.L., Alencar, A.A., Rudorff, B.F.T., Hasenack, H., Matusmoto, M., Ferreira, L.G., Souza-Filho, P.W., et al. (2020). Reconstructing three decades of land use and land cover changes in Brazilian biomes with Landsat archive and Earth Engine. Remote Sens. *17*, 2735. https://doi.org/10.3390/rs12172735.

71. Potapov, P., Hansen, M.C., Pickens, A., Hernandez-Serna, A., Tyukavina, A., Turubanova, S., Zalles, V., Li, X., Khan, A., Stolle, F., et al. (2022). The global 2000-2020 land cover and land use change dataset derived from the landsat archive: First results. Front. Remote Sens. *3*, 856903. https://doi.org/10.3389/frsen.2022.856903.

72. Descals, A., Wich, S., Meijaard, E., Gaveau, D.L.A., Peedell, S., and Szantoi, Z. (2021). High-resolution global map of smallholder and industrial closed-canopy oil palm plantations. Earth Syst. Sci. Data *13*, 1211–1231. https://doi.org/10.5194/essd-13-1211-2021.

73. Fagan, M.E., Kim, D.-H., Settle, W., Ferry, L., Drew, J., Carlson, H., Slaughter, J., Schaferbien, J., Tyukavina, A., Harris, N.L., et al. (2022). The expansion of tree plantations across tropical biomes. Nat. Sustain. *5*, 681–688. https://doi.org/10.1038/s41893-022-00904-w.

74. Harris, N., Dow Goldman, E., and Gibbes, S. (2019). Spatial Database of Planted Trees (STDP, Version 1.0) (World Resources Institute).

75. Wang, Y., Hollingsworth, P.M., Zhai, D., West, C.D., Green, J.M.H., Chen, H., Hurni, K., Su, Y., Warren-Thomas, E., Xu, J., and Ahrends, A. (2023). High-resolution maps show that rubber causes substantial deforestation. Nature *623*, 340–346. https://doi.org/10.1038/s41586-023-06642-z.

76. Food and Agriculture Organisation of the United Nations (FAO) (2020). Global Forest Resources Assessment (FAO).

77. Hajjar, R., Oldekop, J.A., Toto, R., Alencar, L., Bell, S.D., Devenish, K., Khuu, D., Hernández-Montilla, M., Jung, S., Nofyanza, S., and Sapkota, L.M. (2025). Data challenges in socioeconomic impact assessments of conservation regimes. Conserv. Biol.

78. den Braber, B., Oldekop, J.A., Devenish, K., Godar, J., Nolte, C., Schmoeller, M., and Evans, K.L. (2024). Socio-economic and environmental trade-offs in Amazonian Protected Areas and Indigenous Territories revealed by assessing competing land-uses. Nat. Ecol. Evol. *8*, 1482–1492. https://doi.org/10.1038/s41559-024-02458-w.

79. Chi, G., Fang, H., Chatterjee, S., and Blumenstock, J.E. (2022). Microestimates of wealth for all low- and middle-income countries. Proc. Natl. Sci. Acad. USA *119*, e2113658119. https://doi.org/10.1073/pnas.2113658119.

80. Sherman, L., Proctor, J., Druckenmiller, H., Tapia, H., and Hsiang S. (2023). Global high-resolution estimates of the United Nations Human Development Index using satellite imagery and machine learning. NBER Working Paper Series 31044. https://doi.org/10.3386/w31044

81. Kummu, M., Kosonen, M., and Masoumzadeh Sayyar, S. (2025). Downscaled gridded global dataset for gross domestic product (GDP) per capita PPP over 1990-2022. Sci. Data *12*, 178. https://doi.org/10.1038/s41597-025-04487-x.

82. Niva, V., Horton, A., Virkki, V., Heino, M., Kosonen, M., Kallio, M., Kinnunen, P., Abel, G.J., Muttarak, R., Taka, M., et al. (2023). World's human migration patterns in 2000-2019 unveiled by high resolution data. Nat. Hum. Behav. *7*, 2023–2037. https://doi.org/10.1038/s41562-023-01689-4.

83. Garnett, S.T., Burgess, N.D., Fa, J.E., Fernández-Llamazares, Á., Molnár, Z., Robinson, C.J., Watson, J.E.M., Zander, K.K., Austin, B., Brondizio, E.S., et al. (2018). A spatial overview of the global importance of Indigenous lands for conservation. Nat. Sustain. *1*, 369–374. https://doi.org/10.1038/s41893-018-0100-6.

84. Ru, Y., Blankespoor, B., Wood-Sichra, U., Thomas, T.S., You, L., and Kalvelagen, E. (2023). Estimating local agricultural gross domestic product (AgGDP) across the world. Earth Syst. Sci. Data *15*, 1357–1387. https://doi.org/10.5194/essd-15-1357-2023.

85. Weiss, D.J., Nelson, A., Gibson, H.S., Temperley, W., Peedell, S., Lieber, A., Hancher, M., Poyart, E., Belchior, S., Fullman, N., et al. (2018). A global map of travel time to cities to assess inequalities in accessibility in 2015. Nature *553*, 333–336. https://doi.org/10.1038/nature25181.

86. UNEP-WCMC and IUCN (2024). The World Database on Protected Areas (UNEP-WCMC). www.protectedplanet.net.

87. Cazalis, V., Princé, K., Mihoub, J.-B., Kelly, J., Butchart, S.H.M., and Rodrigues, A.S.L. (2020). Effectiveness of protected areas in conserving biodiversity. Nat. Commun. *11*, 4461. https://doi.org/10.1038/s41467-020-18230-0.