https://doi.org/10.1038/s44168-026-00353-7

Towards a multilevel modelling framework for coproducing feasible and equitable portfolios of land-based climate mitigation technologies

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Land-based mitigation technologies and practices (LMTs) are central to climate policy scenarios that limit global warming to below 2 °C and ideally 1.5 °C by reducing carbon dioxide emissions and enhancing carbon dioxide removals from the atmosphere. Reliable estimates of their mitigation potential are essential for informing climate policies across spatial scales and governance levels. However, assessments must move beyond maximum technical potential to account for environmental constraints, social equity, competing land uses and barriers to large-scale deployment. We argue for an analytical framework that integrates numerical modelling with stakeholder engagement in integrated transdisciplinary analyses. This approach enables equitable coproduction of knowledge and supports a deeper understanding of the complex interactions between social and environmental processes that shape the implementation and governance of LMTs, thereby improving their realistic contribution to climate change mitigation and broader socioeconomic objectives.

Land-based mitigation technologies (LMTs) in the Agriculture, Forestry and Other Land Use[1] sector play a central role in climate-policy measures aimed at limiting warming to below 2 °C or even 1.5 °C. LMTs reduce emissions or enhance carbon removal by increasing the amount of carbon stored in vegetation and soils[1–4], with examples ranging from emission-reducing practices, such as bioenergy crops[5], fire management[6] and peatland restoration[7,8], to removal-focused approaches, such as afforestation, reforestation and conservation agriculture[9].

Global scenarios, however, often rely heavily on large-scale biomass production for bioenergy combined with carbon capture and storage (BECCS). While these deployments can be considered a viable route for achieving stringent 1.5 °C targets from a technological-economic standpoint[10], they are criticised for their high land demand, competition with food production and biodiversity and uncertain technical and political feasibility[11,12]. Large-scale land-use shifts can disproportionately affect regions with weaker land rights, lower institutional capacity, or limited political influence, shifting burdens onto those least responsible for emissions[13,14]. Recognising these justice-related dimensions is essential for evaluating the realistic contribution of LMTs to mitigation pathways.

Estimating realistic LMT contributions is crucial for informing climate policy across spatial and governance levels[1]. Local actors, such as farmers, often focus on immediate, context-specific options, e.g. integrating biofuel crops or improving grasslands, that provide livelihood benefits[15]. Policymakers tend to prioritise long-term national carbon-sequestration strategies[16]. Across levels, such strategies must account for feasibility, societal acceptance, trade-offs with food security and biodiversity and the durability of carbon storage[17–20]. The incorporation of justice- and equity-related considerations, as highlighted by the shortcomings of current global 1.5 °C scenarios, is increasingly recognised as central to designing socially acceptable mitigation[21,22].

While feasibility and acceptance can be assessed from a social-science perspective, numerical models remain essential for identifying suitable

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locations for LMTs, e.g. by estimating carbon-storage potential, and assessing land-use trade-offs, e.g. between food production, climate mitigation and the preservation of biodiversity[23]. However, models alone may overlook questions of equity and justice, such as who bears opportunity costs or whose priorities shape scenario assumptions. A climate equity approach is needed in scenario development that broadly considers the impacts and risks of climate change on diverse populations[24].

To address these conceptual gaps, we introduce epistemic justice into our research process[25] by including individual stakeholders' knowledge (epistemology) and lived experiences rather than depending solely on traditional engagement[26], in which stakeholders validate researchers' assumptions. The focus on stakeholders' epistemologies changes the research process, shifting it from a researcher-centric scientific process to one in which the research team engages in equitable knowledge coproduction (EKC) with stakeholders[27]. EKC is a transdisciplinary method that we apply in our study. It represents a means to bring together researchers, practitioners and stakeholders in problem formulation, incorporating their diverse knowledge and using it to interpret results and design modelling experiments together. The meaningful inclusion of stakeholder knowledge in creating scenarios can help identify barriers to LMT implementation and any injustices that may occur in the scaling up of LMTs. Thus, climate equity requires the inclusion of a diverse group of stakeholders, including those most (adversely) impacted by climate actions or technologies, when scenarios are formulated. In essence, we adopt an equity or 'difference' approach[28], which recognises the unique needs of various individuals and groups (e.g. by gender or socioeconomic situation) and considers a unique combination of LMTs according to local social and environmental constraints and their mitigation potential in the scenario development process.

The inclusion of stakeholder knowledge and epistemologies is particularly important, as many studies focus on a single spatial level or a narrow set of LMTs without considering the potential trade-offs that may impact surrounding communities and the environment[29]. Global scenario studies often follow a top-down approach centred on long-term mitigation targets[30–32], with limited attention given to how feasible or just these targets are at the local level[13,14]. Bottom-up studies are rare, and both approaches typically rely on literature and statistical data rather than local or stakeholder knowledge[31,33].

Recent IPCC assessments underscore the importance of strengthening this cross-level integration. The 1.5 °C report highlights the role of feasibility, governance and institutional capacity in determining whether mitigation measures can be implemented in practice[34]. The IPCC Land Report further emphasises that the cross-scale and cross-sectoral nature of LMTs requires multilevel governance and deeper stakeholder engagement to coordinate decisions across levels[35]. Stakeholder insights are also critical for understanding how inequalities shape the barriers to effective land-based mitigation, particularly because many of the greatest challenges and greatest potential benefits lie in the Global South, where land tenure insecurity, uneven power relations and capacity gaps raise important justice concerns[36]. Addressing such heterogeneity requires a systems-level understanding of stakeholders' roles, interests and constraints to ensure that LMT pathways and scenarios advance rather than undermine equity and social justice[37].

From this perspective, we argue that advancing the assessment of LMTs requires (1) combining top-down and bottom-up modelling approaches and (2) actively engaging stakeholders throughout the modelling process. Such integration is essential not only for capturing the complex social–environmental interactions that shape LMT implementation but also for addressing the justice and equity dimensions that influence how benefits, burdens and risks are distributed across communities. To this end, we propose a novel analytical framework that combines numerical models and structured forms of stakeholder participation, enabling transdisciplinary analyses that draw on both scientific expertise and stakeholders' empirical knowledge across diverse social, economic and environmental contexts. 'Stakeholders' here refers primarily to decision makers who directly influence LMT implementation, such as farmers, foresters, planners, investors and policy makers. We view this framework as a way to improve the conceptual and empirical understanding of LMT feasibility, effectiveness and global upscaling potential while also supporting more equitable and context-appropriate implementation on the ground.

The remainder of the paper develops this analytical framework. First, we identify the relevant modelling levels and explain why LMT portfolios and stakeholder engagement are essential, including for recognising justice- and equity-related constraints and opportunities. Second, we review previous approaches to modelling LMTs across spatial scales. Third, we present our framework for integrating models with equitable stakeholder coproduction to assess feasible, equitable LMT targets and their mitigation contributions. We conclude with a discussion of the research challenges involved in establishing such a framework. While the methodological core of the manuscript lies in advancing our multilevel modelling and stakeholder coproduction framework, another key objective is to enhance global-level climate mitigation studies, in which Integrated Assessment Models (IAMs) currently play a pivotal role in informing global policy[38].

Multiple levels and codesign of LMT portfolios

Consideration of multiple levels

In our analytical framework, we distinguish four levels of modelling (Fig. 1): local/landscape, national/regional, continental and global. On these levels, relevant analyses, policies and the corresponding institutions and decisions concerning the establishment of LMTs are developed. Examples include the global Paris Agreement (global level), the European Union climate law (continental level), Nationally Determined Contributions[39] (NDCs) (national/regional level), and their implementation by farmers and foresters through climate-smart agricultural and forest-management practices (local/landscape level).

Rather than viewing these levels as isolated entities, we propose considering cross-scale linkages in our analysis. To connect local LMT studies to the global level on which IAMs operates, we introduce an intermediary continental narrative perspective. This continental perspective plays a pivotal role in translating bottom-up insights into top-down global assessments. It links the local and national to the global level by integrating the technical and feasible mitigation potential of LMTs as well as regional barriers, risks and capacity gaps that shape the implementation of LMT portfolios. By establishing this narrative layer, the continental level becomes more than an administrative category; it becomes a key analytical bridge that connects regional realities and introduces them into global climate scenarios.

The need to establish such linkages becomes evident when examining the disconnect between levels in the implementation of the Paris Agreement. While global climate-mitigation goals should translate into NDCs, the aggregated current NDCs still fall short of achieving the Paris goals[40]. Moreover, the magnitude of this ambition gap is substantial for many high- and medium-income countries but not for low-income countries, raising significant justice and equity concerns[41]. A further disconnect exists between national policies and local needs. At the local level, for instance, households may prioritise immediate needs, such as employment, over longer-term decarbonisation goals[42].

The global models used to inform international climate policies tend to neglect this small-scale variability, focusing instead on the technical potential of mitigation strategies to achieve long-term priorities but often failing to capture what can realistically be achieved 'on the ground'[31]. In contrast, highly resolved local models may be too context-specific, overlooking national priorities, such as economic development and broader environmental or biodiversity considerations. To overcome these disconnects, we consider the combination of level-specific models linked through mechanisms that facilitate the cross-level exchange of data, assumptions and information together with a strong continental narrative layer as essential elements of our analytical framework.

From single LMTs to LMT portfolios

Instead of focusing solely on the technical potential of LMTs, in the context of our framework, we understand the feasible potential as the socially and

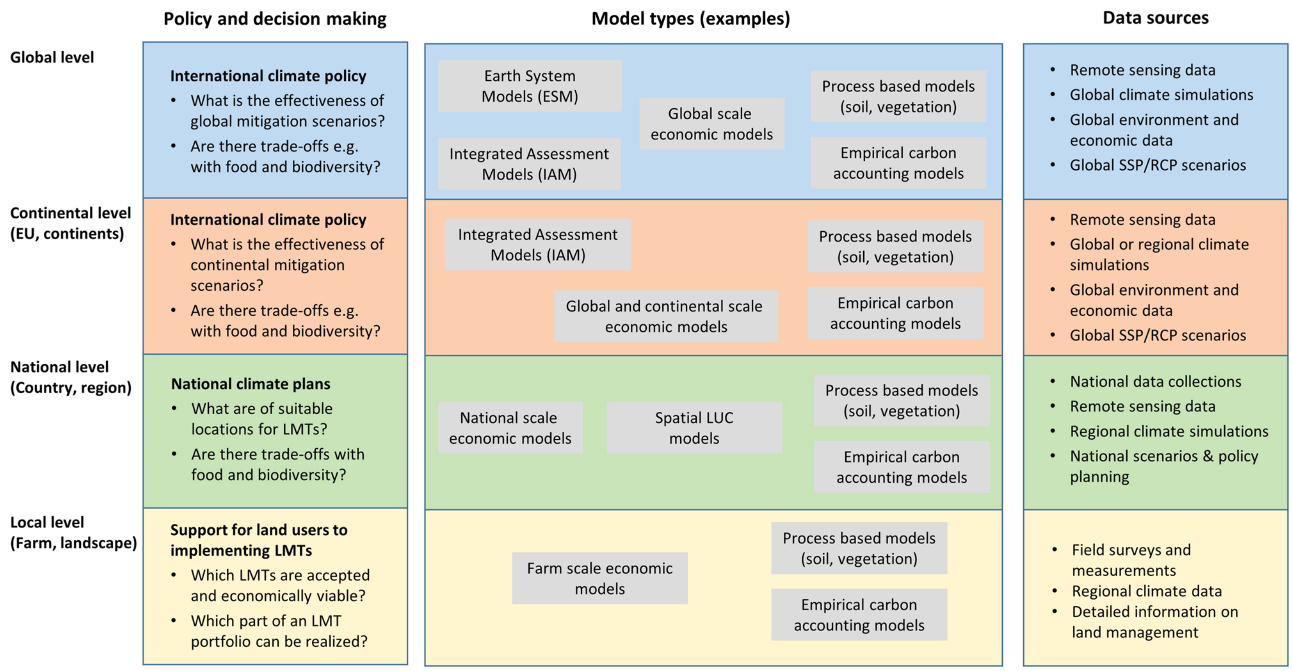

Fig. 1 | Application of models to support policy and decision-making at different levels. The box on the left-hand side summarises important goals and information demands of policy and decision makers regarding the implementation of LMTs on four levels. The middle box shows examples of model types used to provide information to help answer these questions. The box on the right-hand side gives an overview of the data sources used for modelling.

politically acceptable level of LMT deployment that can realistically be achieved with the resources available at a given level, including finance, labour, institutions, technology and knowledge. Determining this feasible potential requires accounting for ecological, societal, technological and institutional constraints[12,29,43] as well as dynamic changes in resource demand and availability. Rather than assessing individual LMTs in isolation, the feasible potential should be evaluated for portfolios of multiple LMTs. Such a portfolio-based approach enables the analysis of a broad spectrum of climate-change-mitigation options, including their synergies and trade-offs with other land-use goals. Moreover, it supports a better balance between emission-reduction and carbon-removal targets and promotes more efficient resource allocation, thereby enhancing potential benefits while minimising risks or unintended negative outcomes of LMT implementation.

What combinations of LMTs should we consider in modelling experiments?

We argue that a feasible LMT portfolio cannot be determined by modellers alone, as modelling exercises often rely on idealised simulation settings that overlook regional variability and focus narrowly on optimising technical solutions[10,31]. Instead, feasible portfolios should be developed through bottom-up processes that (1) incorporate diverse societal interests and policy priorities across different levels and (2) account for overlapping competition and trade-offs among LMTs. The development of a robust local understanding of LMTs prior to scaling them up is essential if we are to avoid overestimating their overall potential. For example, an LMT portfolio that proves viable when scaled up from a single farm may be ecologically or economically unsuitable in another region within the same country.

One way to derive feasible LMT combinations for a specific scale is to cocreate LMT narratives with stakeholders who are knowledgeable about, or directly responsible for, implementation. Stakeholder engagement may involve workshops, focus groups, or interviews[44]. Through this process, our portfolio approach integrates research evidence with stakeholder-derived narratives to identify the most feasible combinations of LMTs. In this context, a narrative serves as a descriptive framework that captures stakeholders' perceptions of how a sector or technology is currently evolving and how it is expected to develop in the future[45].

Combining equitable stakeholder coproduction and models across levels

For instance, at the local level, the codevelopment of narratives of LMT portfolios includes the engagement of a wide range of stakeholders, including farmers, local land use managers, planners and local policy makers. Farmers and local land use managers possess lived experiences and knowledge sometimes inherited from previous generations. Recognising the local and experiential knowledge of these diverse stakeholders (i.e. recognition justice) as legitimate knowledge in and of itself without having a need to add scientific framing to this knowledge to provide it 'scientific legitimacy' promotes epistemic justice not only in our research practices but also in how knowledge is presented for decision makers[25].

Stakeholder groups also do not have homogenous identities. Therefore, we must consider applying an intersectionality lens during equitable stakeholder coproduction processes to ensure that the results of models contribute to LMT policies that are equitable, inclusive and responsive to the diverse experience of the affected at the community or regional levels. Intersectionality[46] helps us understand how overlapping identities — such as gender, ethnicity, socioeconomic status, age and geographical location — affect individuals' access to decision-making processes. A critical starting point is understanding key questions such as the following: Who is recognised, affected or impacted by the proposed LMT scaling-up measures? Which vulnerable groups, such as women, indigenous communities, or those in marginalised regions, will be more strongly impacted? Are there legal and institutional mechanisms in place to protect the rights and ensure the equality of human and nonhuman actors, including ecosystems and different species? We also must consider whether there is fair representation in stakeholder coproduction processes. Are stakeholders able to participate freely and safely, with full rights? Are we ensuring that all voices — especially those of the historically excluded — are meaningfully included in scenario development and narrative framing? Finally, it is essential to recognise and respond to people's diverse needs, identities and interests. Engaging through an intersectional approach moves beyond tokenistic inclusion towards genuine empowerment and justice in land-based mitigation actions.

Each stakeholder, with their intersectionality, has different perspectives and knowledge, such as how they understand the land and local ecosystem with respect to the feasibility of land management practices and policy goals for climate mitigation and biodiversity conservation. On the basis of the knowledge coproduced in this process, models can be used to upscale these portfolios, including local knowledge from the plot level to the national level, and to calculate their mitigation potential. Incorporating a range of stakeholder perspectives is especially important in the case of LMTs because of their heterogeneity and, especially, the distinction between engineered solutions (ES) and nature-based solutions. The different technologies and measures relate to substantially different social values and conceptualisations of spatial domains[47]. Thus, the inclusion of stakeholders' knowledge and epistemologies promotes climate equity in modelling and analysis by including LMTs and/or spatial and socioeconomic constraints that might otherwise be missed or obscured.

Modelling of LMTs and portfolios

Numerical models, evaluated and calibrated against empirical observations and stakeholder knowledge, represent our best quantitative understanding of how different LMTs can affect carbon storage in soils and vegetation. Provided with scale-specific input data from various sources, these models can help answer questions related to LMT implementation and support policy and decision-making at different levels (Fig. 1).

Models that quantify avoided emissions or additional carbon uptake from implementing individual LMTs or LMT portfolios can be integrated with models that situate these results within a broader context, for example, by incorporating economic boundary conditions or trade-offs related to food production, societal consumption patterns and nature conservation. At the global level, Integrated Assessment Models (IAMs) play a central role in providing such overarching perspectives[38]. The different components of this modelling landscape and how they interact across scales are further elaborated in the following parts of this section.

Modelling carbon stocks and flows

Models for calculating carbon stocks and flows are essential for determining the extent to which LMTs contribute to climate change mitigation. The complexity of these models ranges from relatively simple empirical approaches[48] to detailed process-oriented biogeochemical models[49–51].

An example of an empirical model is the IPCC Guidelines for National Greenhouse Gas Inventories[52]. Here, a set of factors derived from field measurements is used to determine carbon storage in soils and vegetation under different land management practices. Changes in carbon storage are determined by comparing two points in time, before and after the establishment of a new management practice[23]. Empirical models offer the advantages of being easily accessible (often in the form of spreadsheet applications or spatial landscape models, such as ALCES[53], that link landscape composition to carbon storage via coefficients) and demanding less data than biogeochemical models do. Their short runtimes facilitate fast and flexible analysis of LMT portfolios, making them appropriate tools for stakeholder codevelopment processes. An notable disadvantage is that the effects of future climate change cannot be estimated adequately by such models because empirical data for future circumstances are mostly nonexistent[54].

Biogeochemical models simulate the processes that drive the growth and decomposition of vegetation and soil carbon pools. The build-up and loss of carbon pools react dynamically to external climatic variables, such as temperature or soil moisture[55]. This process-oriented approach makes the model results more robust than the purely statistical upscaling of empirical data. Because most of these models include rate modifiers that scale with changing environmental conditions, it is possible to estimate the stability of newly established carbon pools under climate change conditions. Simulations typically require very detailed input data, such as daily weather, historical land use and fertiliser inputs, which at different spatial levels are subject to their own uncertainties[56]. Examples of biogeochemical models applied for studying LMTs include LPJmL[57–59], LPJ-GUESS[32,60,61], RothC[50,62,63], DNDC[51,64], DayCent[49,65] and CENTURY[66].

Application for analysing LMTs and portfolios on different levels

In principle, empirical and biogeochemical models can be applied at each spatial level, as they are one-dimensional point-level models. Upscaling to the national or global level is commonly implemented by the application of these models on grid points. Such grid points are independent of each other and must be supplied with boundary conditions, for instance, where an LMT is located or how many external inputs, such as manure, are applied. Hence, they answer questions about the technical potential of LMTs[49,50] and where a specific LMT has the greatest potential[31,67,68]. To address questions of economic and societal feasibility or land-use competition, these models are often coupled with spatial land-use models[23] or economic models[48,69], which provide information on the aforementioned boundary conditions or determine the locations of LMTs within a region as inputs for calculating carbon pool changes. This combination of models may be beneficial for policy makers because in addition to providing information on climate change mitigation it also represents the economic trade-offs and resource competition that are necessary to determine the feasible LMT potential.

On the farm and landscape level, biogeochemical models are applied, for example, to assess the effects of soil conservation measures on soil organic matter[70]. Empirical models are used for calculating the carbon sequestration of agroforestry systems in the Sahel region in combination with a model to account for economic profitability[71] and for soil-vegetation carbon stock accounting, in this case coupled with an agent-based bioeconomic model to portray farmers' decision-making[72].

At the subnational and national levels, the majority of studies have assessed either the carbon storage potential of forests[20,73–76] or agricultural management. Here, the investigated practices include the cultivation of cover crops[50], increased manure utilisation[62,77], reduced tillage[23], the utilisation of crop residues[67] and grassland management[68]. Because these studies neglect competition between different LMTs and other land uses, they have only limited utility for assessing the feasible countrywide climate change mitigation potential. There are only several studies that consider LMT portfolios. A case study for France couples an economic model and an empirical model to analyse different agricultural LMTs[48]. Another interesting example of a portfolio analysis applied the LPJ-GUESS model in Kenya and Ethiopia to compare different agricultural LMTs under current and future climates, identifying the LMT that was most suitable for each area[78].

On the continental and global levels, examples of using biogeochemical models include analyses of single LMTs, such as reduced tillage[58,79], crop residues[64] and the introduction of cover crops[59]. Global studies that consider LMT portfolios apply such models for analysing soil carbon sequestration of different agricultural practices[57,63] or in the selection of the 'most effective' LMT from a set of given alternatives[31].

Cross-level analysis: Integrated Assessment Models (IAMs)

In contrast to the modelling approaches discussed in earlier subsections, there are relatively few examples outside the IAM community that integrate models across multiple spatial levels. One such exception is the nested modelling study by Schaldach et al., which analysed soil-carbon sequestration from land-management changes in Brazil[80]. IAMs typically couple energy-system and socioeconomic models operating at the level of world regions with environmental components, such as vegetation or land-use models that often run on gridded spatial units[81]. Recent applications include the calculation of land-use patterns and greenhouse gas (GHG) and aerosol emissions[81,82] for scenarios used by global Earth System Models in the CMIP6 multimodel experiment[83], which provided the scientific foundation for the IPCC AR6 reports[84]. CMIP6 scenarios were developed exclusively by experts[10] by combining shared socioeconomic pathways with representative concentration pathways, thereby spanning a broad range of socioeconomic and radiative-forcing futures. Although IAMs operate across multiple scales, they follow a predominantly top-down perspective and represent societal and land-management variability only in coarse terms[85]. Therefore, from our perspective, IAMs are limited in their ability to assess the feasible potential of LMTs, an assessment that requires stronger representation of

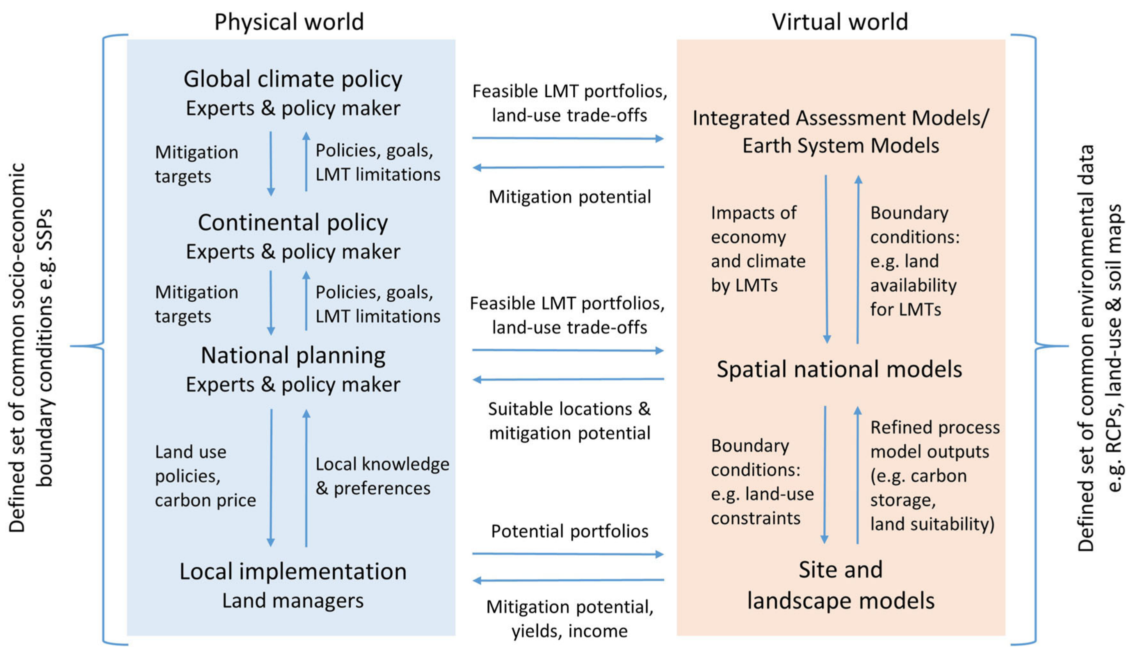

Fig. 2 | Concept of our multilevel modelling framework. In this example, we differentiate four levels (local, national, continental and global). At each level, we identify decision makers and their goals regarding the establishment of feasible LMT portfolios (physical world) as well as models that provide information to decision makers, e.g. regarding suitable areas for implementation and mitigation potential (virtual world). In addition, the framework facilitates the integration of data, information and knowledge across scales by providing communication interfaces between models (virtual world) and by engaging stakeholders in the process of problem formulation and the design of modelling experiments.

local realities, constraints and stakeholder knowledge and epistemologies to adequately confront climate equity challenges. To address this limitation, IAMs must be complemented with finer-scale models and qualitative information that capture regional diversity more accurately. This assumption is consistent with the conclusions of Low et al., who argue that, beyond technical model improvements, creating 'more points of access to codesign' is essential for integrating justice and equity considerations into IAMs[86].

Concept of a multilevel modelling framework for assessing feasible LMT portfolios

The main objective of our framework is to facilitate the model-based analysis of the feasibility and mitigation potential of LMT portfolios and to support decision-making on their implementation across different levels (Fig. 2).

Our modelling framework builds on three main elements: (1) decision makers and models at the four individual levels (local, national, continental and global), (2) methods for the integration of data, information and knowledge across scale levels and (3) methods for equitable stakeholder coproduction in problem formulation and the design of modelling experiments. The framework enables the application of different, already existing model types and provides mechanisms for structuring and organising the interplay between decision makers, models and the inclusion of diverse stakeholders' knowledge. To strengthen the link between detailed local analyses of LMTs and the global dynamics captured by IAMs, we propose the introduction of an intermediary continental-level narrative perspective.

Decision makers and models at the individual level

At each of the four levels, we identify decision makers and their goals related to the LMT portfolios as well as a set of models from among the options presented in the previous section. These models can provide information that contributes to answering specific questions of decision makers related to their goals. An example of a decision-maker at the local level would be a land manager (e.g. a farmer) who considers applying one or multiple LMTs. This LMT could be, for example, no-tillage on cropland, which produces sufficient yields to sustain a stable income and simultaneously increases the soil carbon content. The increased carbon stock might then translate into carbon credits as a supplementary income source[87,88]. A combination of models to help answer questions of income, crop yields and carbon storage could comprise a biogeochemical model and an economic model[71]. In contrast, at the national level, the decision maker might be a ministry official who is interested in assessing how LMT portfolios could reduce GHG emissions as part of a national climate plan[89]. Here, questions regarding trade-offs between different land uses are relevant, including ensuring food production and nature conservation. In this case, a model system could comprise a spatially explicit land-use model and an empirical carbon model[23].

Integration across levels

In our understanding, a multilevel analysis integrates data, information and knowledge across levels. An example could be the matching of mitigation targets at the national level with potentials to implement feasible LMT portfolios at different locations within the country. For this type of analysis, we propose combining bottom-up and top-down approaches. A purely bottom-up approach would first analyse LMT portfolios, for instance, with a biogeochemical model for a set of farms that represent a diversity of economic and environmental conditions. In the second step, upscaling to the national level could be performed with a variety of methods[90,91], e.g. with software tools such as geographic information systems, to identify available areas for implementation and then simulate the potential carbon uptake of these areas with a biogeochemical model. In contrast, a top-down analysis, such as that conducted with IAMs, would start with a national target for reducing GHG emissions and storing additional carbon and downscale these targets by allocating LMTs to locations with suitable soil types and topography to grow crops or trees but without considering detailed local socioecological boundary conditions[92,93]. Interestingly, Roe et al.[33] show that owing to different underlying data and modelling approaches, the results of the bottom-up and top-down methods do not necessarily align. Combining these two approaches, a modelling experiment using our framework would include the local findings and upscaled information as boundary conditions to represent the spatial heterogeneity of constraints and preferences for LMT portfolios in a more detailed manner than in top-down-only analyses.

At higher levels, a global modelling study can consider national and continent-specific policies with respect to goals of and limitations on LMT implementation or acceptance. In turn, a national-scale analysis would account for international boundary conditions and developments as well as local knowledge (see example above). In this type of cross-level analysis, it is important to use unified sets of socioeconomic boundary conditions and environmental data whenever possible to ensure consistency at the individual level (see outside brackets in Fig. 2). This includes similar assumptions for prices for agricultural commodities and carbon pricing as inputs for economic models[94] as well as consistent land-use[81] and climate datasets[82], e.g. as inputs for crop growth and land use models.

Equitable stakeholder coproduction for operationalising multi-level analysis

We have already noted the role of EKC with stakeholders in codesigning LMT portfolios. In addition, there are other strong arguments for codeveloping knowledge with stakeholders actively in modelling studies. When such studies are informed by stakeholders' knowledge and epistemologies, they can more accurately explore the feasibility of short- and long-term implementation within a level-specific context, as they reflect local knowledge regarding land management and the societal acceptance of LMTs[95,96]. Moreover, equitable stakeholder coproduction in the construction of scenarios to explore future development pathways could help increase the relevance of these scenarios[97] and contribute to trust building and greater acceptance of different LMT portfolio implementations. Here, a key consideration is the range of stakeholders included, such as indigenous communities and civil society groups, whose involvement broadens participation and enriches the perspectives informing the analysis. In this sense, EKC with stakeholders can aid in selecting the relevant LMT based on the local context rather than on theoretical potential and in better qualifying (e.g. by ranking or weighing) perceived synergies and trade-offs (i.e. consensus formation associated with the implementation and upscaling of individual or multiple LMTs). For decision makers, the coproduction of knowledge with stakeholders can help raise questions that are more socially and economically relevant and to structure and analyse model results so that they are useful for policy-making processes. In the following section, we discuss different formats, challenges and limitations for stakeholder integration, particularly those linked to multilevel analyses.

The way forwards: challenges and research requirements

Benefits of combining top-down and bottom-up approaches

Our proposed framework combines models operating at different levels. Linking top-down and bottom-up approaches is key in this context since this enables the exchange of data, information and knowledge across scales. Both approaches have their own benefits and drawbacks. We believe that using them in a complementary manner will improve LMT scenario analyses. Data integration as well as equitable stakeholder coproduction are some of the techniques to prioritise for achieving beneficial synergies. While equitable stakeholder coproduction could provide new insights into data and model integration across multiple levels, data integration needs may, in turn, shape the design and outcomes of stakeholder coproduction processes, particularly those focused on eliciting information that is not well codified.

Challenges of equitable stakeholder coproduction in multilevel analysis

Recent modelling studies explore inconsistencies in CO_2 fluxes and managed forestland areas[98], discuss different assumptions and modelling frameworks[99] or apply land-use conversion rates on the basis of historical data[100]. While these studies are important, they often do not consider the social and economic feasibility of LMTs or the potential opportunities envisioned by stakeholders, including land managers, supply-chain (market) stakeholders associated with each LMT and policy makers.

We argue that enlisting the input of such stakeholders to create a regional overview of LMT portfolios is essential to developing pathways that are realistic and feasible and that avoid overreliance on technical potential that often cannot be fully realised because of social, economic, political, environmental, or policy barriers and constraints[1]. Continental narratives codeveloped with stakeholders and modellers can help set the broader pathway direction (e.g. targets/goals), boundaries (e.g. feasible LMT growth potential) and contextual conditions (e.g. market and ecological limitations) of an LMT portfolio pathway. Along with complementary information from literature reviews, this approach can serve as a basis for enriching input into global models by linking the local and global levels. Participatory scenario planning with stakeholder coproduction has been used in previous modelling exercises, e.g. research focusing on a smaller region and on the national level. Such examples include studies on regions in Russia[101] or northern Ghana[102]. Participatory foresight methods have also been used in studies in which scenario development is combined with quantitative modelling at the global level[103]. The missing link we have found in the literature between the local and the global is to consider the continental context as a core focus of narrative developments that can feed into global modelling processes.

Identifying feasible LMT portfolios

To integrate suboptimal LMT portfolios that are feasible at the local level with optimal strategies at the global level, it may be necessary to consider a range of factors, such as economic, social and environmental trade-offs. Multicriteria decision analysis could be applied, which involves the systematic evaluation of different options on the basis of a set of criteria[104] to better consider the needs and priorities of diverse stakeholders. For instance, we can use the criteria identified by stakeholders and the literature at the national level as a starting point for engaging with stakeholders at the continental level. This process would include a continental perspective when modelling at the global level.

Modelling stakeholder needs and priorities by considering stakeholder knowledge in the modelling process is a complex task, as stakeholders often hold diverse and conflicting interests and values[105]. Multiple forms of sovereignty over land resources intersect, and the growing involvement of international actors in financing and implementation makes the application of principles of equity across different levels of negotiation particularly important for ambitious land-based mitigation efforts[106]. Equity considerations are also critical when LMT portfolios are integrated at different levels with different stakeholder groups[1], since scaling up LMTs can exacerbate existing inequalities and vulnerabilities within communities.

The risk of injustice intensifies with large-scale LMT deployment. IAMs suggest high feasibility for interventions such as afforestation/reforestation (AR), BECCS and forest management in regions of Asia, Africa and Latin America, regions that have historically contributed less to climate change[33]. Global-scale BECCS deployment may require up to 910 million hectares[107], much of which land is located in tropical countries where land availability is limited, tenure is often insecure and governance is challenged by corruption, land grabbing and land-use conflicts[14]. While large-scale deployment could create new actors or strengthen existing capacities in biomass supply chains, it may also intensify competition with other land uses, such as food production and nature conservation, potentially threatening biodiversity, raising food prices and undermining food and livelihood security for resource-poor farmers[1]. Thus, assessing LMT feasibility must be coupled with climate equity considerations, including restorative justice, to address past harm and prevent future inequities[108]. This involves acknowledging historical land-use impacts on local communities and implementing reconciliation measures for indigenous peoples affected by colonial oppression and extractive resource development[109].

The global extent of degraded land in the world is estimated at ~2 billion hectares[110], which is more than twice the projected land requirements for BECCs or other carbon removal approaches. Climate equity concerns associated with large-scale LMT deployment can be reframed in the context of restoring degraded lands, as returning these lands to productive use typically enhances biodiversity and increases carbon sequestration. The diverse stakeholders engaged in these restoration processes can provide valuable insights into opportunities for new livelihoods and cobenefits arising from associated LMTs.

The critical processes identified in this paper emphasise the importance of ensuring that diverse stakeholders (i.e. recognition justice[111]) and their knowledge (i.e. epistemic justice[25]) are respected in decision-making. Evaluating the benefits and costs of different LMT options through an equity lens is essential. EKC with stakeholders involves assessing the potential impacts of LMT interventions on vulnerable or historically marginalised groups and implementing measures to redress past harm and prevent future harm (restorative justice[108]). This includes making recommendations to avoid potentially negative effects[27] and ensuring that restoration and LMT implementation contribute to socially just and sustainable outcomes.

Conclusion

We have delineated the concept of a modelling framework to explore options for LMTs at different levels. This approach represents an important step towards a more comprehensive understanding of the limitations of LMT implementation while considering equitable stakeholders' knowledge to support the feasibility of technologies at a higher level[112]. Our framework builds on the combination of previously developed modelling tools and connects these tools with elements of EKC with diverse stakeholders. Therefore, our framework's general design is applicable to different study settings. For example, policy-oriented large-scale modelling activities at the regional or European Union level or global assessments such as the UNEP Global Environmental Outlook[113] might benefit from knowledge at the regional or local level gained by individual research projects, with the goal of developing a more detailed and better informed picture of land-based climate change mitigation potential.

Data availability

No datasets were generated or analysed during the current study.

Received: 18 June 2025; Accepted: 11 February 2026;
Published online: 25 February 2026

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Acknowledgements

This work was supported by the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 869367 (LANDMARC).

Author contributions

R.S. and J.L. wrote the main manuscript text and prepared the figures. J.L., M.X., L.K. and F.X.J. elaborated and wrote the sections about stakeholder

involvement. R.S., E.T., M.G.D. and M.L. wrote the sections about modelling of LMT portfolios. R.S., J.L., M.X., M.L., E.T., E.A., M.C., M.G.D., D.I., F.X.J., L.K., J.O., E.S. and F.W. contributed to the conceptualisation of the proposed modelling framework as well as to the initial stucturing and the final review of the manuscript and figures.

Funding

Open Access funding enabled and organized by Projekt DEAL.

Competing interests

The authors declare no competing interests.

Additional information

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