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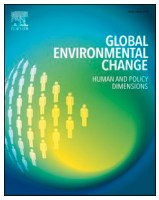

Land-use spillovers from environmental policy interventions

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ABSTRACT

Environmental policy interventions are crucial for addressing biodiversity loss and climate change, yet their effectiveness can be compromised by land-use spillovers, where efforts to reduce impacts in one place displace them elsewhere. Despite growing recognition of spillovers, they remain unevenly defined, inconsistently measured, and poorly integrated into policy evaluation and accountability frameworks. This systematic review synthesizes current research on land-use spillovers triggered by environmental policies, including carbon pricing, protected areas, supply chain interventions, and payments for ecosystem services. We identify three dominant pathways: leakage, indirect land use change (iLUC), and positive spillovers, emerging under common conditions such as weak enforcement, market integration, limited livelihood alternatives, and accessible frontier lands. These conditions are shaped by broader institutional, economic, demographic, and biophysical drivers, yet are rarely integrated into policy design and evaluation. While methods to evaluate spillover effects range from global scale ex ante models to local ex post spatial and econometric analyses, few studies bridge scales or connect findings to international policy frameworks such as the Convention on Biological Diversity (CBD) or the United Nations Framework Convention on Climate Change (UNFCCC). Cases are concentrated in climate-linked interventions and in South America, leaving important geographic and sectoral blind spots. This limits their relevance for designing policies that minimize displaced impacts and foster more durable outcomes. Advancing spillover research will require common frameworks, more consistent methodologies, and multi-scale tools that can enhance comparability, attribution, and integration into environmental governance.

1. Introduction

Amid escalating global environmental challenges, policies aimed at mitigating deforestation, conserving biodiversity, and reducing greenhouse gas emissions have become central to international and national agendas (Chan et al., 2023). Global efforts to address these pressing challenges require coordinated action and robust policy frameworks (Arneth et al., 2020; Shin et al., 2022). The Kunming-Montreal Global Biodiversity Framework (GBF), under the Convention on Biological Diversity (CBD), and the United Nations Framework Convention on Climate Change (UNFCCC) play pivotal roles in addressing these mounting, interdependent pressures by targeting biodiversity loss and climate change, respectively (Affinito et al., 2024; Allan and Bhandary, 2024). From conservation programs and zero-deforestation commitments to payments for ecosystem services (PES) and trade regulations, these climate- and biodiversity-related interventions aim to address critical environmental challenges while balancing economic and social priorities (Boran and Pettorelli, 2024). However, despite setting ambitious goals, global efforts to halt biodiversity decline and counter climate change have often fallen short of their intended targets, raising concerns about the effectiveness of existing policy interventions (Carroll et al., 2024). While these interventions aim to improve sustainability outcomes, their effectiveness is often influenced by unanticipated or collateral effects, including negative land-use spillovers such as leakage and indirect land-use change (iLUC). Leakage occurs when interventions aimed at reducing environmental impacts in one place, context or sustainability dimension produce adverse changes or increased impacts in another beyond the policy's jurisdiction (Meyfroidt et al., 2020; Streck, 2021), while iLUC refers to shifts in land use caused indirectly by market and behavioral changes (Wicke et al., 2012). These phenomena are further amplified by the telecoupled nature of land systems, where actions and events in one region can substantially impact distant regions

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(Liu et al., 2018). For instance, conservation policies such as deforestation bans may protect forests in regulated areas but displace agricultural pressures to less-regulated regions, exacerbating land-use conflicts (Meyfroidt and Lambin, 2009). Similarly, supply-chain commitments designed to reduce environmental harm can inadvertently lead to land conversion in areas with weaker regulations (Garrett et al., 2021). Despite growing awareness of the adverse effects of global sustainability targets (Pe'er et al., 2020), their design often overlooks the complexities of land systems—dynamic socio-ecological systems shaped by competing demands for agriculture, forestry, conservation and livelihoods (Meyfroidt et al., 2022). As a result, negative land-use spillovers can undermine or even negate the intended environmental benefits of policy interventions by displacing economic activities or triggering land-use changes outside the targeted areas, ultimately reducing their overall effectiveness (Meyfroidt et al., 2020). Understanding these spillover effects has been the focus of a growing body of literature (Atmadja and Verchot, 2012; Miteva et al., 2012; Pfaff and Robalino, 2017; Ostwald and Henders, 2014; Fuller et al., 2019; Lewison et al., 2019; Meyfroidt et al., 2020), which proposes various methodological approaches to assess the impacts of environmental policy interventions, with particular emphasis on land-use spillovers such as leakage (Streck, 2021; Filewod and McCarney, 2023) and iLUC (Henders and Ostwald, 2014). Despite progress in understanding the drivers of land-use spillovers, critical knowledge gaps persist (Meyfroidt et al., 2020). Many studies primarily assess the intended, direct impacts of environmental policies, such as reductions in deforestation or emissions within the regulated areas (Oestreicher et al., 2009; Almer and Winkler, 2017; Lambin et al., 2018), while giving less attention to the broader, land-use spillovers these policies may induce (Atmadja and Verchot, 2012; Pfaff and Robalino, 2017). Moreover, the pathways through which spillovers occur, particularly the underlying conditions and mechanisms, remain underexplored (Meyfroidt et al., 2020). Factors such as policy enforcement and market integration play pivotal roles in shaping the extent and nature of leakage (Robinson et al., 2013; Cavanagh et al., 2015; Berning and Sotirov, 2023), while global market dynamics can either amplify or mitigate spillovers depending on their interaction with local policies and economic contexts (Filewod and McCarney, 2023; Lambin and Furumo, 2023). Importantly, not all spillovers are negative; some may result in net-positive outcomes, yet the conditions that differentiate these outcomes are poorly understood (Fuller et al., 2019). Furthermore, the limited synthesis across policy types and geographic contexts constrains the ability to generalize findings and apply them to new interventions (Lewison et al., 2019).

Here, we synthesize current knowledge on land-use spillovers resulting from environmental policy interventions, based on a systematic literature review of studies that conduct either ex post or ex ante evaluations. First, we identify the spillover effects linked to these interventions and the methodologies employed in their evaluation. Next, we examine the common conditions and mechanisms driving these outcomes. Finally, we illustrate the connections between interventions, conditions and observed land-use spillovers to better visualize the pathways leading to these outcomes. This review intends to highlight the challenges of effectively evaluating and anticipating the secondary effects associated with environmental policy interventions, with a particular focus on the land-use spillover effects such interventions may generate. We seek to contribute to ongoing discussions about how science can better inform policymaking, ensuring that policies not only mitigate negative outcomes but also proactively include anticipatory tools to guide decision-making towards sustainable pathways. After presenting the results in Section 3, we will discuss the challenges and opportunities of using scientific insights to design and implement more informed policies.

2. Methods

We conducted a systematic literature review to examine the land-use spillover effects of environmental policy interventions, emphasizing empirical evidence from peer-reviewed scientific studies. This approach ensures the inclusion of expert-evaluated evidence, providing a robust foundation for exploring the conditions and the mechanisms driving land-use spillovers and for documenting the methods used in their assessment. The review incorporates both ex ante and ex post case studies across diverse policy instruments, including climate mitigation and biodiversity conservation interventions, implemented within various environmental frameworks and agreements. To ensure comprehensive coverage of studies within the scope of our review, we employed an iterative two-step search strategy. First, we queried the Web of Science and Scopus databases using predefined Boolean search terms, including "leakage", "spillover", "land use displacement", and "indirect land use change", combined with "biodiversity", "conservation", "intervention", and "land use change". To refine this initial search, we applied the Rapid Automatic Keyword Extraction (RAKE) algorithm available in the *litsearchr* R package (Grames et al., 2019). This algorithm identifies frequently co-occurring phrases and synonymous terms within scientific texts, allowing us to evaluate and expand the comprehensiveness of our initial search terms. Based on the RAKE outputs, we iteratively updated the search query to include additional relevant terms until we were confident that the search strategy captured the relevant literature (for details of the iterative refinement process and the final search terms, see Supplementary Material S1, Table 1, Text 1 and Fig. 1). Searches were confined to titles, abstracts, and keywords, and the final search was conducted in December 2024, yielding a total of 1,488 articles, with 477 identified as duplicates. After retrieval, we screened abstracts according to predefined inclusion criteria to enable a consistent analysis of the findings afterwards. The criteria include: (a) environmental policies were defined as interventions aimed at achieving environmental benefits, including biodiversity conservation, climate change mitigation, and the sustainable management, restoration, or use of natural resources. This definition encompassed measures such as protected areas, sustainable agricultural practices, community forest management concessions, carbon pricing mechanisms, and payments for ecosystem services. Policies promoting sustainable intensification were included if explicitly tied to environmental objectives, given their relevance to climate and land-use challenges. Interventions without primary environmental goals, such as general agricultural subsidies, were excluded unless their spillover effects were directly relevant to land-use dynamics and environmental outcomes; (b) studies needed to clearly identify the policy instrument(s) under evaluation and directly assess their impact on relevant outcomes, such as leakage or indirect land-use change (iLUC); (c) ex post studies were required to use causal inference methods capable of establishing causality (e.g., randomized controlled trials, natural experiments, difference-in-differences, instrumental variable approaches) and ex ante studies needed to explicitly model policy impacts on land-use outcomes rather than simply incorporating iLUC factors in life cycle assessments; (d) studies were required to provide clear and replicable descriptions of their methodology, including data sources, spatial and temporal scales, and analytical techniques; (e) studies explicitly measuring or discussing land-use spillover effects, including spatial or temporal spillovers, were included; (f) studies needed to describe the contextual conditions and potential mechanisms through which spillovers emerge; (g) studies that conducted literature reviews, focused solely on life cycle impact assessments without addressing driving factors, contextual conditions, and causal mechanisms, or provided purely theoretical analyses without empirical evidence were excluded. Finally, only publications dated since 2000 were included, as studies on land-use spillovers and their evaluation methodologies became more prominent after this period.

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist was employed to document the selection process (Supplementary Material S2). We screened and coded the selected studies to categorize the types of policy interventions, types of land-use spillovers associated with policy interventions, the factors

moderating the conditions that could lead to such outcomes, the mechanisms through which they emerge, and the methods employed for their evaluation. To categorize land-use spillovers, we adhered to the definitions proposed by the land system science community (Meyfroid et al., 2018; Meyfroidt et al., 2020). These definitions provide a consistent framework for understanding land-use spillovers within the field of land system science. In this context, land-use spillovers are understood as processes through which changes in land use or direct interventions in land use in one location impact land use in another location (Meyfroidt et al., 2020). The categories we use to characterized land-use spillovers include 1) leakage, a type of land-use spillover caused by an environmental policy, which reduces the overall effectiveness of the intervention; 2) indirect land-use change (iLUC), where land use change in one place is caused by land use change in another place; 3) land-use displacement, where causal attribution to a given policy or intervention is not sufficiently strongly established, 4) positive land-use spillovers or "boosting effects". To identify the conditions that foster land-use spillovers and the mechanisms driving them, we categorized the underlying drivers into broad groups: demographic, economic, technological, institutional, sociocultural, and location/environmental factors. These categories were further refined into subcategories based on common themes and definitions found in the literature, with specific variables identified for each. We also analyzed how these conditions influence spillovers, assessing whether factors amplify (e.g., "high market integration," "uneven enforcement") or mitigate (e.g., "high compliance," "limited land accessibility") their occurrence (Supplementary Material S3). This allowed us to link observed conditions that increase susceptibility to land-use spillovers with the processes through which they manifest and their effects. The encoding process also involved determining whether the studies assessed land-use

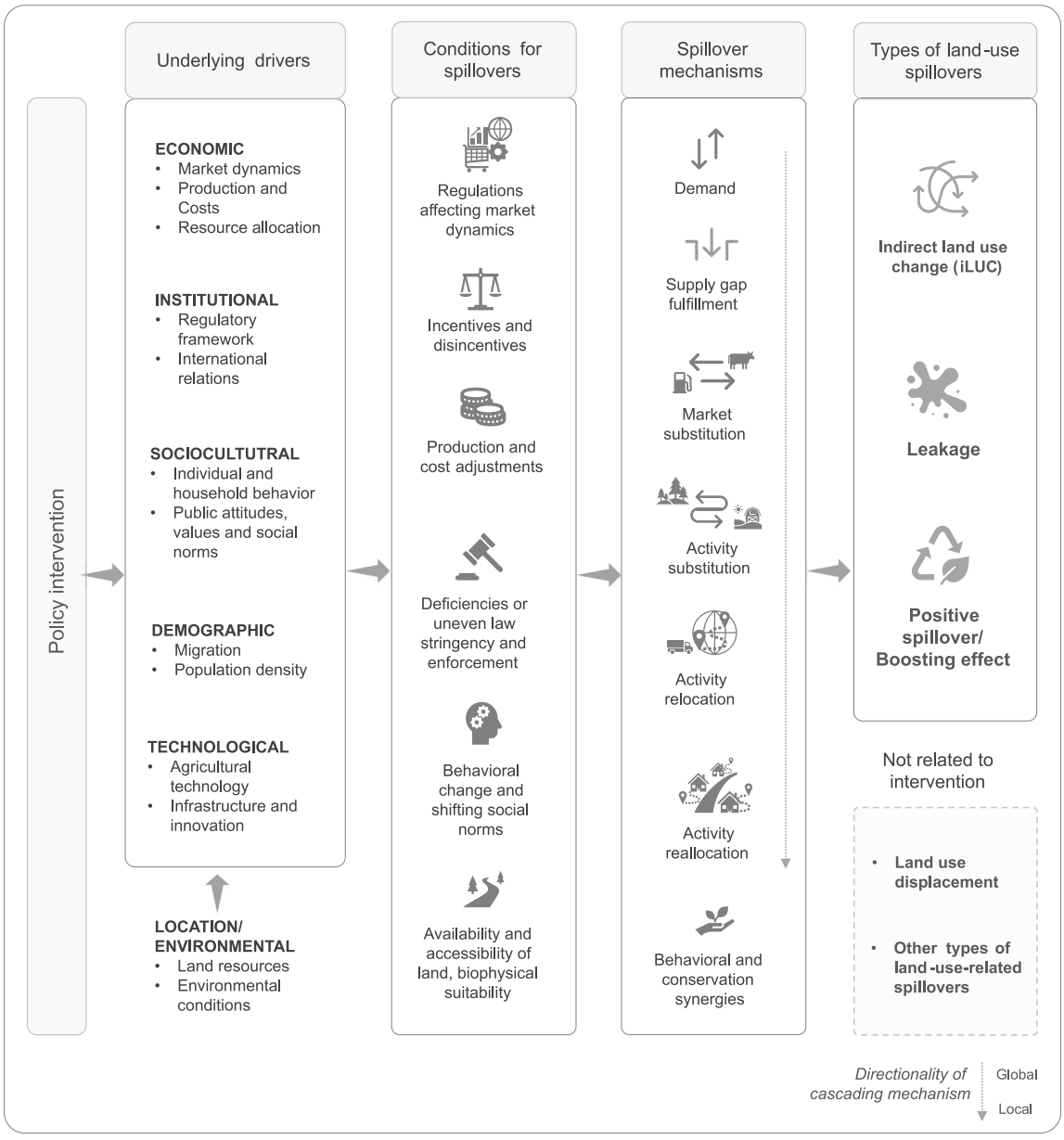

Fig. 1. Conceptual framework illustrating the pathways through which policy interventions may lead to land-use spillovers. The framework links underlying drivers (economic, technological, institutional, sociocultural, demographic, and environmental) to spillover mechanisms via intermediary conditions, such as regulations, price incentives, and behavioral adaptations. These interconnected mechanisms (e.g., demand shifts leading to market substitutions and activity relocations) create cascading effects that propagate across regions and scales, resulting in various land-use spillovers, including indirect land-use change (ILUC), leakage, and positive spillovers (boosting effects).

spillovers within various environmental frameworks or mechanisms, such as REDD + and the Clean Development Mechanism, as well as global environmental conventions, namely the CBD and UNFCCC. We conducted an iterative review and refinement of the coding for selected studies, establishing categories for type of policy intervention, type of land-use spillover, conditions that foster land-use spillovers and the mechanisms through which they emerge, and evaluation methods (Supplementary Material S1, Tables 2–3 & Supplementary Material S3). Each case was assigned a unique ID. A case refers to a unique combination of a policy intervention type, a land-use spillover outcome, a location analyzed independently, and a publication. If a study analyzes the land-use spillover effects of different policy configurations within an intervention, each configuration is treated as a separate case (Supplementary Material S3). The selected studies offered insights into three research questions: 1) What is the current state of scientific knowledge on land-use spillovers from environmental policy interventions? 2) What methods have been used to evaluate land-use spillovers from environmental policy interventions? 3) Under what conditions and through which mechanisms are land-use spillovers more likely to emerge? Our overarching goal was to deepen our understanding of the collateral consequences resulting from policy interventions, offering recommendations for both the scientific and policy domains.

2.1. Pathways to land-use spillovers: Linking conditions to mechanisms and spillover effects from environmental policy interventions

Based on the reviewed studies, we developed a conceptual framework to illustrate the pathways through which policy interventions lead to land-use spillovers (Fig. 1). The framework consists of four stages. The first stage outlines the underlying drivers, including economic (e.g., market dynamics, production costs), technological (e.g., agricultural innovation), institutional (e.g., regulations, enforcement), sociocultural (e.g., public attitudes, social norms), demographic (e.g., migration, population density), and environmental factors (e.g., land resources). These drivers shape how policies interact with socio-economic and ecological systems. The second stage identifies conditions created or altered by policy interventions that increase the likelihood of spillovers. Key factors include regulations affecting market dynamics, price incentives, production and cost adjustments, enforcement capacity, behavioral adaptations, and land suitability and accessibility. These conditions create pathways for spillovers by modifying local responses to interventions. The third stage describes the interconnected mechanisms through which spillovers occur. These include demand changes, supply gap fulfillment, market substitution (e.g., biofuels replacing pastures), activity substitution (e.g., shifting from forestry to agriculture), and relocation or reallocation of activities. Activity relocation refers to the displacement of an activity, such as deforestation or agriculture, from one geographic area to another—often to avoid regulatory constraints or capitalize on opportunities in less-regulated regions. In contrast, activity reallocation occurs within the same entity and reflects a redistribution of resources or land use between different land categories (e.g., shifting from regulated private lands to unregulated common property lands within the same community). These processes are inherently tied to the spatial boundaries defined in the analysis and influence how spillovers are interpreted. For example, relocation typically indicates a failure to mitigate broader land-use impacts, whereas reallocation reflects localized shifts that could be addressed through targeted regulatory mechanisms. These interconnected mechanisms (e.g., demand shifts leading to market substitutions and activity relocations) create cascading effects that propagate across regions and scales, resulting in various land-use spillovers. The fourth stage categorizes the outcomes of these spillovers as indirect land-use change (ILUC), leakage, or positive spillovers. We use this framework to map the pathways leading to land-use spillovers as described in the reviewed studies, providing insights into how policy interventions shape land-use dynamics across different contexts.

3. Results

3.1. Extent of existing evidence on land-use spillovers arising from environmental policy interventions

We identified 58 studies that met our selection criteria by using sufficiently rigorous methods to evaluate land-use spillovers and by describing the conditions and mechanisms through which these spillovers emerge (Fig. 2). From the selected studies, we identified 92 unique cases examining land-use spillovers resulting from policy interventions, 16 of which reported no significant spillover effects. Most studies have focused on economic/market-based policies, which account for 41 % of the cases. These policies include tradable permits (e.g., certified emissions reductions), taxes and charges (e.g., carbon tax), and subsidies and incentives (e.g., payment for environmental services) (Fig. 2b). Area-based conservation policies, such as protected areas, represent 20 % of the cases. Meanwhile, zero deforestation supply chain interventions implemented through market exclusion mechanisms like the Amazon Soy Moratorium and G4 Cattle Agreement, comprise 12 % of the cases. Studies assessing land-use spillovers from biofuel policies (e.g., Mandates and Standards) make up 8 % of the cases. Direct regulation policies, such as forestry bans, along with land use zoning, participatory management, and certification, account for 11 %, 3 %, 3 %, and 2 % of the cases, respectively. We identified diverse terms used to evaluate land-use spillovers emerging from environmental policy interventions, often linked to their spatial expression (Supplementary Material S3). Studies describe spillovers across various levels, using terms such as within-farm leakage (Jack and Santos, 2017), within-property leakage (Alix-Garcia et al., 2012), or intra-community leakage (Giudice et al., 2019; Carrilho et al., 2022) and within-community leakage (Eisenbarth et al., 2021). At broader spatial scales, spillovers are categorized as cross-biome leakage (Gollnow et al., 2018; Heilmayr et al., 2020b), cross-border leakage (Villoria et al., 2022), transboundary leakage (Murray et al., 2004; Roopsind et al., 2019), or global spillovers (Gan and McCarl, 2007). In terms of activity types, deforestation leakage is the most commonly studied, describing the displacement of deforestation from regulated to unregulated areas (e.g., Herrera et al., 2019; Heilmayr et al., 2020b). Similarly, carbon leakage, often linked to REDD+ programs or carbon pricing mechanisms, highlights the displacement of emissions between regions or countries (Aaheim et al., 2018). While negative spillovers dominate the reviewed studies, positive spillovers are also documented, such as increased conservation in neighboring areas (Cohn et al., 2014; Ament and Cumming, 2016; Amin et al., 2019; Giudice et al., 2019). The directionality (either positive or negative) and interpretation of spillovers further add to their complexity. While leakage is typically framed as a negative outcome, some studies reframe it as a positive spillover effect, depending on the context. For example, Glomsrød et al. (2011) reinterpret leakage in the context of afforestation projects as beneficial or "positive leakage", highlighting additional carbon sequestration and agricultural intensification outside project boundaries. Temporal land-use spillovers have been mostly addressed in studies providing ex ante evaluations, which explore the timing of emissions reductions and show how initial gains associated to policy interventions may be offset by land-use changes in later periods (Popp et al., 2014; Frank et al., 2015; Lobell and Villoria, 2023). Only one study using ex post evaluations, Alix-Garcia and Gibbs (2017), address temporal spillovers as lagged effects, observing increased deforestation in properties registered under later policy cohorts.

While most studies on indirect land use change (iLUC) focused on biofuel policies, such as the impacts of biodiesel and ethanol production in regions like South America, Southeast Asia, and the European Union (Achten and Verchot, 2011; Havlik et al., 2011; Laborde and Valin, 2012), iLUC effects have also been linked to supply chain interventions, particularly in Brazil and Southeast Asia (Arima et al., 2011; Gollnow et al., 2018; Taheripour et al., 2019). Only two selected studies examine

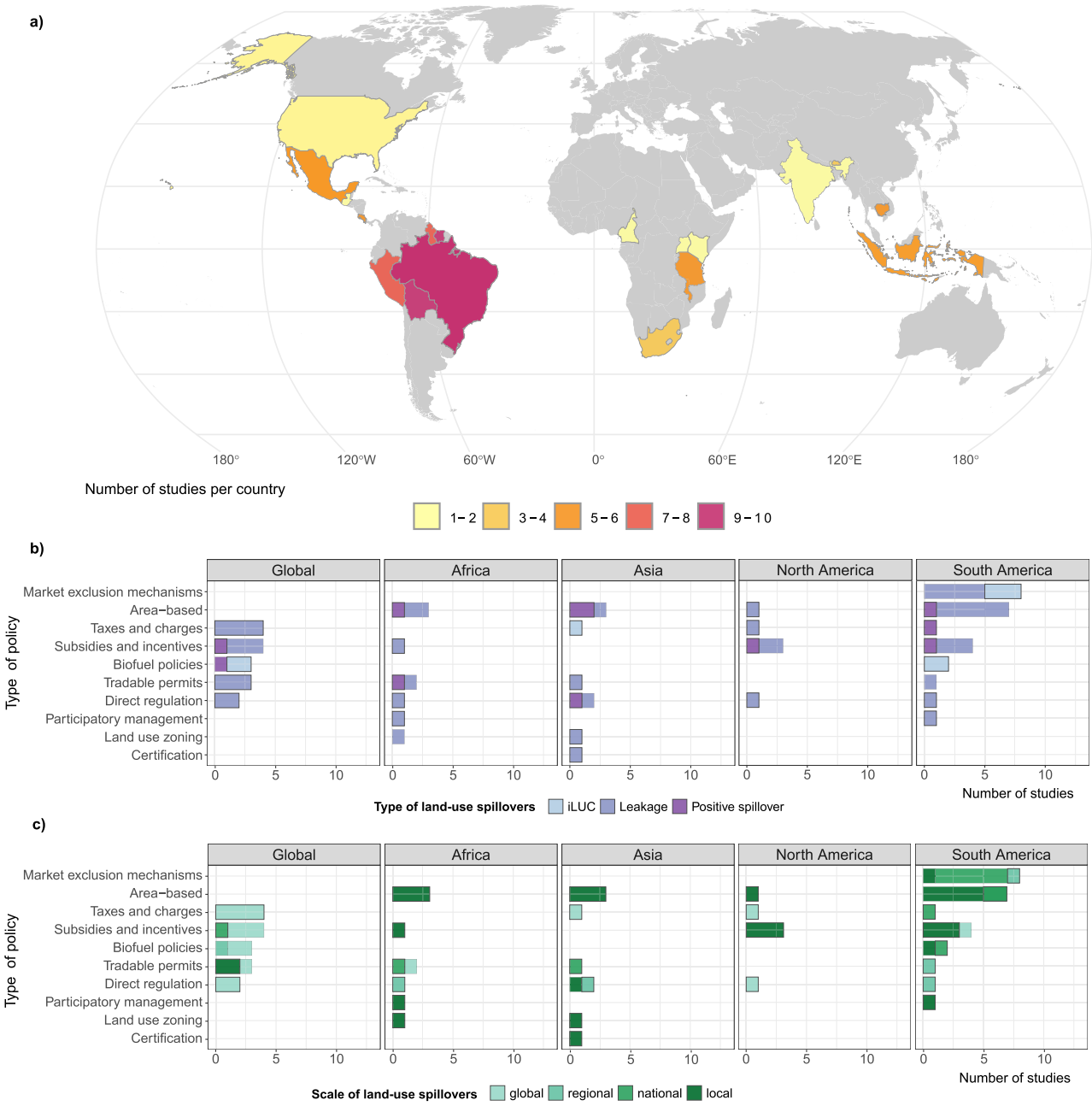

Fig. 2. Overview of studies addressing land-use spillovers in the context of environmental policy interventions: a) Geographical distribution of studies evaluating land-use spillovers by the country where policies were implemented (i.e., the source of spillovers). b) Types of land-use spillovers (iLUC: Indirect land use change, leakage, positive spillover) categorized by policy intervention and region. c) Spatial scale (global, regional, national, or local) at which spillovers were evaluated (i.e., the sink of spillovers), categorized by policy intervention and region.

land use displacement linked to policy interventions, both focusing on direct regulations, such as bans on forest activities: Meyfroidt and Lambin (2009) and Jadin et al. (2016). The former acknowledges both leakage and land use displacement without clear causal attribution, noting policies-trade complexities, while the latter reports a predominantly positive net effect of policies and trade.

The majority of studies examining land-use spillovers in the context of environmental policy interventions do not link their findings to global policy frameworks, often failing to contextualize their results within the broader international conventions or frameworks guiding these policy interventions (Fig. 3). Among those that do, there is a marked emphasis on the UNFCCC and its REDD + mechanism, with studies specifically referencing climate change policies implemented through this framework. In contrast, the Convention on Biological Diversity (CBD) receives considerably less attention, with research primarily exploring spillover effects in protected areas.

3.2. *Methodological approaches for evaluating land-use spillovers from environmental policy interventions*

Studies on indirect land-use change, especially within the biofuel policy domain, have predominantly focused on ex ante assessments using dynamic equilibrium models on a global scale (Fig. 4). These studies aim to identify the market-mediated effects that lead to adverse effects from climate mitigation policies (Lapola et al., 2010; Havlik et al., 2011; Laborde and Valin, 2012). Leakage has been examined

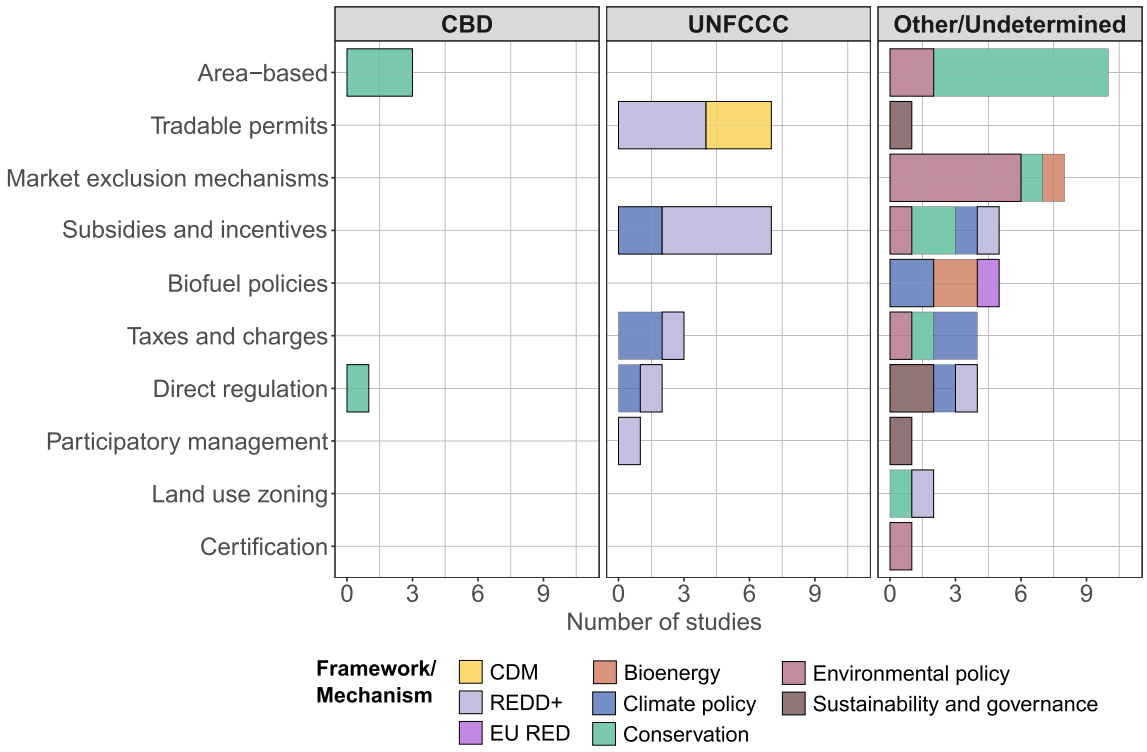

Fig. 3. Scientific studies evaluating land-use spillovers from different types of environmental policy interventions referencing various climate and biodiversity conventions and frameworks. CDM: Clean Development Mechanism, EU RED: European Union's Renewable Energy Directive, REDD+: Reducing Emissions from Deforestation and Forest Degradation. Other/Undetermined: Includes studies that do not explicitly reference major climate or biodiversity conventions but are framed within a general environmental policy context. These studies focus on broader themes such as sustainability, governance, and environmental policy without direct attribution to specific frameworks.

through ex ante and ex post assessments using a diverse array of methods, including dynamic equilibrium models, integrated assessment models, regression models, and spatial autoregressive models. Dynamic equilibrium models have been used to assess ex ante global-scale leakage from national and regional policies (Cohn et al., 2014; Taheripour et al., 2019; Villoria et al., 2022; Fischer et al., 2024). By simulating economic responses to policy interventions, they reveal a potential for significant leakage, albeit with estimates that vary widely (Cohn et al., 2014; Popp et al., 2014; Villoria et al., 2022). One study introduces a global-to-local-to-global (GLG) framework, linking local regulations to global land-use spillovers (Haqiqi et al., 2023). Other studies have explored local-to-global spillovers, such as the effects of climate-smart agricultural policies on emissions (Lobell and Villoria, 2023) and the carbon uptake benefits of protecting Indian plantations (Aaheim et al., 2018).

Studies evaluating ex post land-use spillovers have predominantly focused on market exclusion mechanisms, payments for environmental services, protected areas, community forest concessions, certification, and forestry bans at the local or sub-regional scale. Zero deforestation supply chain interventions, enforced through market exclusion mechanisms (i.e., restricting market access for suppliers associated with unsustainable practices, such as deforestation, Garrett et al., 2022), primarily focus on the Amazon Soy Moratorium and G4 Cattle Agreements in Brazil. These are analyzed at the cross-biome level using a variety of methodologies such as spatial autoregressive models and regression models. Difference-in-differences analysis, including econometric triple-differences model (e.g., Heilmayr et al., 2020b) and spatial boundary approximations (e.g., Moffette and Gibbs, 2021), are also applied. Findings indicate that while deforestation declines within regulated jurisdictions or supply chains, it may increase in neighboring areas lacking such commitments.

Several studies, particularly those focusing on protected areas and payments for environmental services, evaluate spillover effects at the local scale to assess the overall effectiveness of these interventions. Matching and regression techniques, along with difference-in-differences analysis, are widely used to compare regions under conservation policies with those that are not. These studies often apply buffer zones of varying widths around protected areas to assess spillover effects. A common finding is the presence of little to no significant leakage or, in some cases, positive spillover effects ("blockage"), where conservation efforts within protected areas are linked to reduced deforestation in neighboring regions. (Blackman et al., 2015; Herrera et al., 2019).

3.3. Pathways to land-use spillovers: Linking conditions to mechanisms and spillover effects from environmental policy interventions

3.3.1. Land-use spillovers from market-based policies and supply chain interventions

Market-based policies, such as carbon taxes, tradable permits and biofuels mandates, frequently lead to land-use spillovers through two primary pathways: leakage and indirect land-use change (iLUC) (Fig. 5a, Supplementary Material S4). Leakage arises when policies restrict land supply in targeted regions, yet persistent or rising demand shifts production to less-regulated areas (Murray et al., 2004; Popp et al., 2014). ILUC, by contrast, stems not from explicit supply restrictions but from global demand pressures that trigger activity substitution and relocation to new frontiers (Lapola et al., 2010; Arima et al., 2011). For example, biofuel-driven demand has spurred deforestation and agricultural expansion into forested regions worldwide, particularly where enforcement is weak and commodity prices are rising (Lapola et al., 2010; Havlik et al., 2011). Additionally, countries with limited production of certain goods may invest in response to high prices, while farmers in versatile regions may switch to more profitable crops

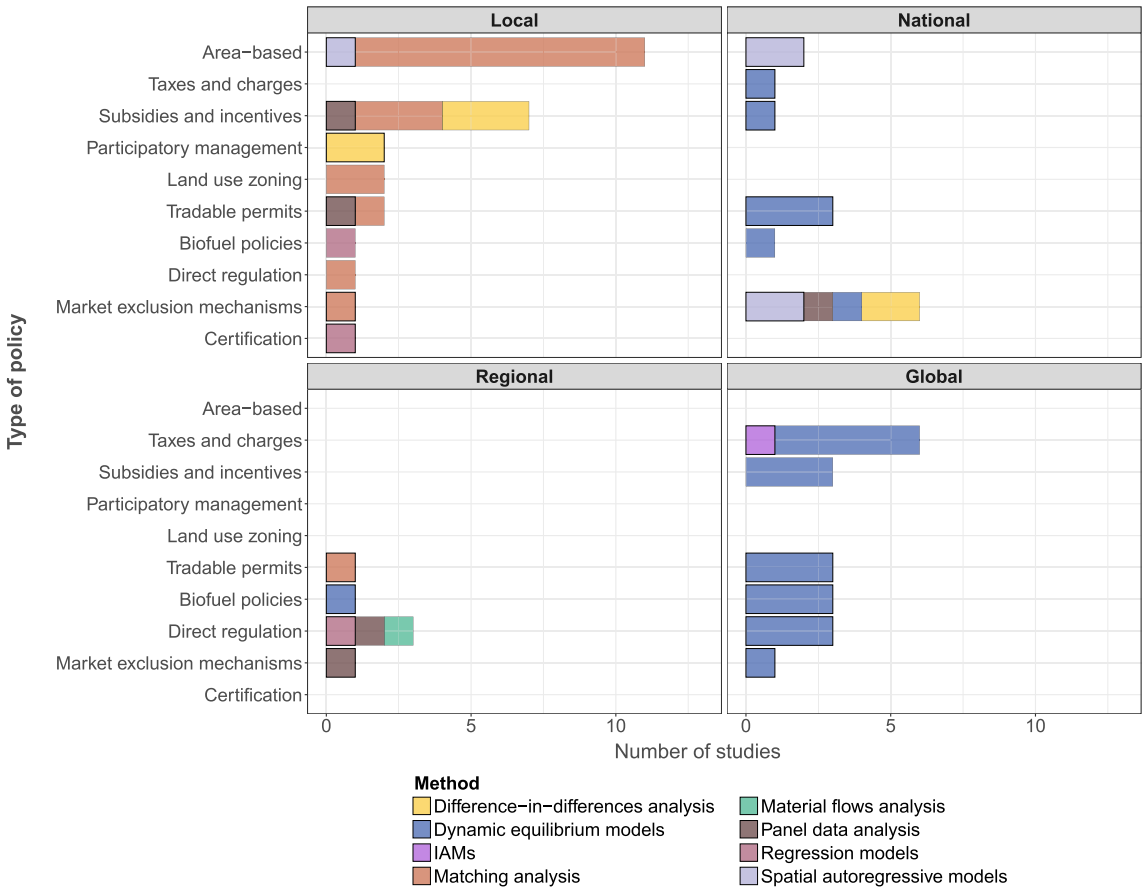

Fig. 4. Scientific studies on methods used to assess land-use spillovers across different spatial scales and types of environmental policy interventions. IAMs: Integrated Assessment Models.

(Taheripour et al., 2019). This dynamic is observed when producers relocate operations to bypass restrictive regulations or to capitalize on lower costs elsewhere, creating land-use spillovers both at regional and global scales (Arima et al., 2011; Dou et al., 2018). Companies affected by new regulations might also relocate their operations to areas with more favorable regulatory environments, leading to direct and indirect land use changes (Kuschnig et al., 2021). Ex ante evaluations project these dynamics on a global scale (Fig. 5a), identifying biofuel mandates as major drivers of agricultural displacement into deforested areas (Havlik et al., 2011; Laborde and Valin, 2012). Such studies also emphasize conditions that mitigate iLUC, such as reinvesting in productivity gains to curb agricultural expansion (Havlik et al., 2011).

Evaluations of agricultural intensification policies, implemented through taxes or subsidies, show mixed land-use spillovers depending on execution. Intensification can promote land sparing by improving productivity on existing farmland, reducing pressure on natural ecosystems (Cohn et al., 2014). For example, fertilizer-driven intensification enhances yields and limits land expansion under optimal nutrient management (Lobell and Villoria, 2023). Similarly, reinvesting economic surpluses from CDM plantations into local economies could amplify land sparing if supported by strong local engagement (Glomsrød et al., 2011). However, ineffective implementation or weak enforcement can trigger activity relocation and land-use spillovers (Haqiqi et al., 2023).

Ex post evaluations on market exclusion mechanisms (Fig. 5b), such as the Amazon Soy Moratorium (ASM) and G4 Cattle Agreement, highlight how these policies restrict deforestation-linked production but create supply constraints, leading to production shifts to unregulated regions or indirect suppliers (Alix-Garcia and Gibbs, 2017; Kuschnig et al., 2021). For instance, the G4 Cattle Agreement in Brazil restricted deforestation on compliant properties, but indirect suppliers operating in unmonitored regions met demand, resulting in local and regional leakage (Fig. 5b, Supplementary Material S4). While these policies reduced deforestation locally, uneven enforcement and persistent demand often drove land-use spillovers across biomes and increased land profitability in less-regulated areas (Alix-Garcia and Gibbs, 2017; Villoria et al., 2022). Studies evaluating land-use spillovers from palm oil certification programs found that programs reduce deforestation in certified areas but often shift production to uncertified regions with weaker environmental safeguards due to weak enforcement, high opportunity costs, and price changes (Heilmayr et al., 2020b; Leijten et al., 2021).

3.3.2. *Land-use spillovers from regulatory and command-and-control interventions*

Ex post evaluations of regulatory and command-and-control interventions, such as bans on resource extraction or land-use activities, show that when bans reduce resource availability in regulated regions, supply gaps are frequently filled through market substitution and activity relocation to less-regulated areas (Fig. 5b, Supplementary Material S4). For instance, Kenya's charcoal ban caused price changes that incentivized production in Ugandan forests near the border, where enforcement was weaker (Bartlett et al., 2024). Similarly, stringent anti-mining policies in French Guiana displaced illegal gold mining to neighboring Suriname, where reduced enforcement costs made extraction more profitable, leading to increased deforestation there (Dezécache et al., 2017). Direct regulations can also yield positive spillovers under certain conditions. Bhutan's roundwood export ban reduced pressure on high-biodiversity forests by shifting timber production to less-sensitive ecosystems in neighboring India, leading to a net-positive ecological outcome (Jadin et al., 2016). However, uneven

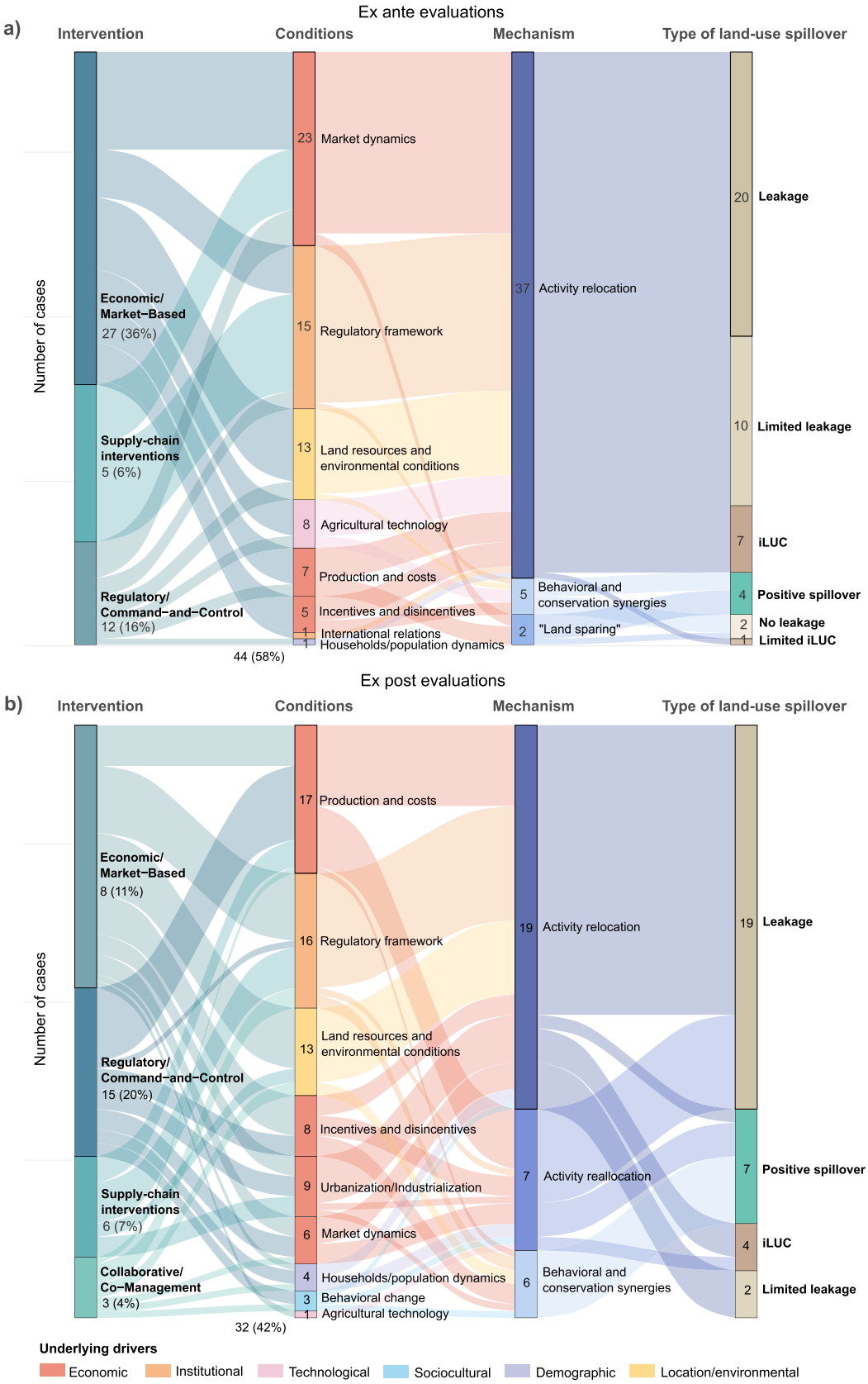

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Fig. 5. Pathways to land-use spillovers. Connections between intervention types, conditions, mechanisms, and resulting land-use spillovers, disaggregated by a) ex ante and b) ex post evaluations. Intervention types (e.g., Economic/Market-Based, Regulatory/Command-and-Control) are influenced by multiple underlying drivers, such as economic, institutional, and environmental factors, which shape the conditions under which interventions are implemented. These conditions, in turn, influence the mechanisms (e.g., activity relocation) through which land-use spillovers emerge, resulting in different outcomes, including leakage, limited leakage, iLUC (indirect land-use change), or positive spillovers. The first column presents the total number of cases by intervention type, with relative proportions shown in parentheses. Absolute case numbers are displayed for each category in subsequent columns (Conditions, Mechanism, and Type of land-use spillover). Each intervention may be associated with multiple conditions (second column), resulting in a higher total number of conditions than the number of unique cases. Each intervention is linked to a single mechanism and a single spillover outcome. Underlying drivers (economic, institutional, technological, sociocultural, demographic, and environmental) are represented through color coding of the Conditions column. Categories such as "limited leakage" and "limited iLUC" refer to cases where spillovers were minimal or negligible (e.g., less than 5% of the observed effect, as reported in the original studies).

enforcement, high market integration, and persistent demand often limit such benefits, with resource extraction shifting to regions with lower regulatory costs or logistical barriers (Meyfroidt and Lambin, 2009).

Protected areas (PAs), a cornerstone of area-based conservation measures, have been evaluated exclusively through ex post analyses of their land-use spillover effects. These studies reveal both positive and negative spillovers, influenced by biophysical (Ament and Cumming, 2016), economic (Robalino et al., 2017), and institutional (Blackman et al., 2015) conditions. For instance, studies across Bolivia, Brazil, Cambodia, and Costa Rica report varied outcomes, ranging from reduced deforestation rates to increased forest loss caused by activity displacement to adjacent non-targeted areas (Blackman et al., 2015; Robalino et al., 2017; Boillat et al., 2022). Positive spillovers often arise when limited accessibility or limited infrastructure development in and around PAs raises the transaction costs of accessing and exploiting natural resources (Robalino et al., 2017). PAs in remote areas can reduce deforestation pressures by making agricultural and logging activities economically unviable (Gaveau et al., 2009; Ament and Cumming, 2016). Additionally, positive conservation spillovers expand when PAs promote ecotourism or conservation clustering, incentivizing nearby landowners to preserve natural land cover through mutually reinforcing behaviors (Ament and Cumming, 2016). Negative spillovers near protected areas (PAs) often stem from land appropriation (Boillat et al., 2022), infrastructure expansion (Robalino et al., 2017), and weak enforcement (Blackman et al., 2015). Poor land tenure incentivizes migrants to clear forests near PAs to establish claims, increasing deforestation on unprotected lands (Herrera et al., 2019; Boillat et al., 2022). The location of PAs also influences spillovers, particularly those near deforestation frontiers or high-profit agricultural zones, where activity relocation shifts deforestation or farming to adjacent areas (Poor et al., 2019). Leakage occurs when activities move from park entrances to less visible areas with greater economic incentives for agriculture or tourism infrastructure (Robalino et al., 2017).

3.3.3. Land-use spillovers within and across communities from payments for environmental services and collaborative/co-management policies

Studies on payments for environmental services and collaborative/co-management policies, such as Payments for Ecosystem Services (PES) and Community Forest Management (CFM) programs, were mostly ex post evaluations (Fig. 5b, Supplementary Material S4). These studies reveal that such interventions frequently result in localized leakage through activity reallocation and behavioral spillovers (Alix-Garcia et al., 2012; Jack and Santos, 2017). Economic incentives often outweigh conservation efforts unless coupled with adequate compensation or sustainable alternative livelihoods that appeal to local communities (Alix-Garcia et al., 2012). In PES and CFM programs, within-property leakage occurs when landowners shift deforestation or agriculture from enrolled to unenrolled areas of their land, often driven by rising agricultural prices due to reduced supply (Alix-Garcia et al., 2012). Additionally, income-boosting programs can increase demand for agricultural goods, making farming more profitable and prompting land expansion. In less populated areas, limited market elasticity amplifies price fluctuations, further intensifying local leakage. As a result, interventions intended for income support can unintentionally reshape agricultural practices and local market dynamics, leading to spillovers within communities (Alix-Garcia et al., 2012; Jack and Santos, 2017). Evidence from Mexico shows that PES programs modestly reduce deforestation but can trigger leakage in high-poverty areas, where deforestation shifts to common property lands (Alix-Garcia et al., 2012). Leakage is also linked to low road density and localized markets with high PES enrollment. In contrast, low-poverty regions exhibit positive spillovers. Another PES field experiment in Malawi found within-farm leakage, where contracted farms increased deforestation instead of reducing agricultural land (Jack and Santos, 2017). Households with surplus land often self-select into PES programs through competitive mechanisms (e.g., auctions) and engage in activities such as tree planting without displacing agricultural land. In contrast, households that received contracts through non-competitive allocation mechanisms (e.g., a lottery) were more likely to experience labor shortages and clear additional land, increasing the risk of within-farm leakage (Jack and Santos, 2017). Behavioral adaptations influence land-use spillovers, as seen in Peru's National Forest Conservation Program (Giudice et al., 2019), where perceived monitoring triggered a Hawthorne effect, the phenomenon where individuals alter their behavior in response to being observed or knowing they are part of a study (Adair, 1984), reducing deforestation in observed areas but not in unmonitored zones. In CFMs, strong enforcement and high transportation costs successfully eliminated leakage by reinforcing incentive-aligned stewardship (Fortmann et al., 2017).

4. Challenges to operationalizing the study of land-use spillovers from policy interventions

Despite advances in defining and categorizing land-use spillovers, a critical gap remains in operationalizing these concepts into measurable, policy-relevant frameworks. The past decade has seen increasing efforts to refine the terminology and understanding of spillover effects (Meyfroidt et al., 2020), yet major challenges persist in measuring impacts and attributing spillovers to specific policy interventions. Key limitations include variability in terminology across disciplines, methodological constraints in quantifying spillover effects, limited empirical evidence from ex post assessments, and insufficient integration of local to global spillovers into methodological approaches and policy evaluations. The need for multi-scale, cross-sectoral frameworks is particularly urgent, given the increasing complexity of land-use dynamics in response to environmental interventions.

4.1. Framing and conceptualizing land-use spillovers

Although definitions of land-use spillovers are well established within certain disciplines, their framing varies based on disciplinary focus, methodological approaches, and policy objectives (Lewison et al., 2019). This review reveals substantial diversity in how spillovers are conceptualized, ranging from localized land-use spillovers (e.g., within-property leakage, Alix-Garcia and Gibbs, 2017) or within-community leakage (Eisenbarth et al., 2021) to broader cross-biome and transboundary leakage (Popp et al., 2014; Villoria et al., 2022). Such differences in framing influence how spillovers are recognized, measured, and integrated into policy responses (Bastos Lima et al., 2019). For instance, economists tend to frame spillovers through a market-based lens,

focusing on price signals and market substitution effects (Filewod and McCarney, 2023). In contrast, conservation researchers conceptualize spillovers based on local ecological impacts (Pfaff and Robalino, 2017). These differences are not merely semantic; they shape how land-use spillovers are assessed and determine whether they are considered negative externalities, neutral shifts, or potential co-benefits (Bastos Lima et al., 2019). A critical challenge lies in ensuring that the diverse forms of spillovers, whether local or global, positive or negative, are adequately recognized in policy frameworks (Ostwald and Henders, 2014; Lewison et al., 2019). Large-scale policy interventions, such as biofuel mandates, deforestation-free supply chains, or conservation incentives, often generate spillovers across multiple scales. These spillovers may be amplified under certain conditions, reinforcing the importance of a common, policy-relevant terminology for evaluating their broader consequences (Pe'er et al., 2020). Developing a practical and reproducible framework requires not only defining spillovers consistently but also identifying where they are most likely to manifest, assessing trade-offs, and anticipating their impacts (Atmadja and Verchot, 2012; Filewod and McCarney, 2023). Harmonizing terminology and adopting integrated methodological approaches are essential to accurately measure, interpret, and address spillover effects in policy design (Hertel, 2018).

4.2. The need for a multi-scale assessment framework

Land-use spillovers rarely stem from a single policy intervention but rather emerge from complex interactions between economic incentives, regulatory frameworks, enforcement mechanisms, and behavioral responses (Atmadja and Verchot, 2012). Despite growing research, the multi-scale nature of spillovers continues to present major challenges for both research and policy. While ex ante assessments often estimate spillovers at global or regional scales (Villoria et al., 2022; Mishra et al., 2024), they lack the spatial resolution to pinpoint where spillovers actually materialize. On the other hand, ex post empirical studies, despite offering valuable insights, remain scarce and tend to focus on specific regions with established monitoring frameworks, such as Brazil (Alix-Garcia et al., 2012; Alix-Garcia and Gibbs, 2017; Heilmayr et al., 2020a). The limited availability of cross-scale studies further constrains our ability to measure, monitor, and anticipate land-use spillovers accurately. A key limitation in existing research is the tendency to evaluate spillovers in isolation rather than as cumulative, interconnected processes (Hertel et al., 2019). Most land-use spillover evaluations focus on deforestation, overlooking impacts on other ecosystems such as grasslands, wetlands, shrublands, and marginal agricultural lands (Csikós and Tóth, 2023). Additionally, these assessments tend to emphasize land conversion while neglecting critical ecological factors such as habitat connectivity, ecological function, and species composition (Pereira et al., 2013; Schmeller et al., 2018). Moreover, many spillover assessments remain highly localized, focusing on deforestation pixels rather than broader landscape-scale connectivity and ecosystem resilience (Brennan et al., 2022). As a result, the broader systemic consequences of spillovers—particularly how localized spillovers scale up to regional or global impacts—are poorly understood. Without accounting for these cross-scale interactions, policy assessments risk underestimating the extent of spillover effects (Hertel, 2018). To address these gaps, an integrated, multi-scale assessment framework is necessary—one that captures both macroeconomic drivers and localized dynamics of land-use spillovers while aligning with broader biodiversity and climate goals (Scholes et al., 2013; Hertel et al., 2019). Such a framework should incorporate spatial resolution at multiple scales (local, regional, and global), account for different types of spillovers (e.g., within-property leakage vs. transboundary spillovers), and consider socio-ecological trade-offs and policy contexts, particularly in balancing conservation and economic objectives. Achieving this requires harmonizing land-use spillover terminology, developing standardized data protocols, and adopting consistent methodologies to enhance cross-study comparisons (Nicholson et al., 2021; Hoban et al., 2022). Additionally, to fully capture spillover impacts, research must move beyond forest ecosystems to include biodiversity-focused indicators and spatial modeling approaches that assess landscape connectivity and ecological resilience (Marsh et al., 2025). Equally important are spatial evaluations that assess trade-offs related to social equity and environmental justice, which remain rare but critical for understanding the broader consequences of policy interventions (Giang et al., 2024).

4.3. Mainstreaming land use spillovers into the environmental agenda

Regions with established monitoring frameworks, such as Brazil, dominate spillover studies, while areas with weaker data infrastructure remain underrepresented. This bias not only skews geographic focus but also highlights broader institutional challenges in global environmental governance. Fragmentation across multilateral agreements, including the CBD and UNFCCC, limits cross-sectoral collaboration, as these frameworks operate under separate monitoring and evaluation procedures (Arneth et al., 2020). To improve policy coherence, biodiversity and climate governance must explicitly incorporate spillover effects into their frameworks. This requires robust indicators, improved data-sharing, and coordinated policy efforts to ensure that conservation and climate mitigation goals are mutually reinforcing rather than conflicting (Pettorelli et al., 2021). Strengthening institutional accountability and fostering collaborative evaluation mechanisms, data-sharing, and mutual learning across sectors and scales will be key to effectively addressing land-use spillovers at multiple scales. We must move beyond simply mitigating spillovers, policy design should proactively transform trade-offs into opportunities for sustainable land-use transitions.

5. Conclusion

Land-use spillovers highlight limitations in how environmental policies are currently designed, evaluated, and monitored, often failing to account for impacts that cross spatial, sectoral, and jurisdictional boundaries. As environmental policies grow in ambition and reach, so too do their spillover effects. Addressing these spillovers will require more than improved measurement; it calls for integrative approaches that connect ecological outcomes with institutional design, social equity, and global sustainability goals. Beyond technical solutions, progress will depend on sustained collaboration between researchers, policymakers, and stakeholders operating across diverse geographies and governance contexts. Strengthening institutional coordination and embedding spillover considerations into policy design, monitoring, and evaluation will be key to minimizing negative outcomes and supporting more coherent and equitable land-use governance.

CRediT authorship contribution statement

Diana Ramírez-Mejía: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Yves Zinngrebe:** Writing – review & editing, Conceptualization. **Erle C. Ellis:** Writing – review & editing, Conceptualization. **Peter H. Verburg:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2025.103013.

Data availability

All data used in this article are available in the supplementary materials

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