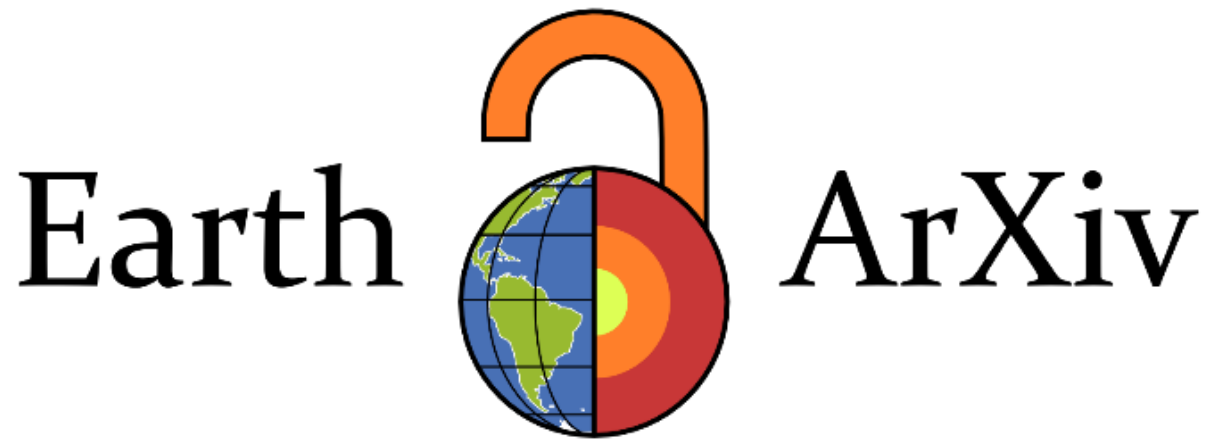




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Land Use Change, Spillovers, and Transitions: Global Trends, Prospects, and Emerging Drivers

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Abstract:

In this review, we first compile data on global trends and rates of major land use changes over the recent decades, and summarize the main insights revealed by these data. We then review recent research and quantitative estimates on key land use spillover processes, i.e., leakage, indirect land use change, rebound effect and land sparing, and agglomeration economies. We then turn to the prospective, by highlighting a few recent processes that may have an increasingly important influence on land use dynamics, and synthesizing recent quantitative projections of global land use dynamics until 2050, discussing business as usual (BAU) trends as well as more transformative scenarios. Extracting high-level lessons from previous research on land use transitions, we bring these different lines of evidence together to synthesize general conclusions about global land use dynamics and how to enhance sustainability through land use.

1. Introduction

Land is a fundamental basis for nature and human life. Land use provides for multiple human needs, which are changing over time, but is also among the most profound ways in which humans impact nature and the Earth system (1, 2). Global

land use trends result from the sum and interactions of myriads of local dynamics and decisions, and, for most impacts, whether environmental (on biodiversity, water, soils, etc, except for greenhouse gas emissions), or human (on food provision, livelihoods, multiple nature's values), it is all these distinct land use changes that matter. Yet, assessing global land use dynamics can provide insights about the general trends of land systems, how local dynamics compensate or reinforce each other, and as such, global land use trends constitute one of the references for assessing the overall success of collective efforts towards transition to more sustainable and just human-environmental relations. Debates about global land use thus reflect and serve as basis for building and projecting narratives and visions about these relations (3).

The objective of this article is thus to assess and discuss recent and projected global trends in land use dynamics, including land use change, spillovers, and transitions. Land use transition has been used for two distinct purposes, to refer to a direct conversion process or to a large-scale, somewhat enduring structural or systemic shift of land use regime (4–6). We will refer to both meanings in this article, the first being used mostly in Section 2, the second in Section 5. This article complements the theoretical synthesis of land use processes in (7), and the synthesis on key facts on land systems and their relevance for sustainability from (2), with further policy elaboration in (8).

This article is organised as follows: In Section 2, we compile data on global trends and rates of major land use changes over the recent decades, and summarize the main insights revealed by these data. In Section 3, we review recent research and quantitative estimates on key spillover processes, i.e., leakage, indirect land use change, rebound effect and land sparing, and agglomeration economies. In Section

4, we turn to the prospective. We first highlight a few recent processes that may have an increasingly important influence on land use dynamics. We then synthesize recent quantitative projections of global land use dynamics until 2050, discussing business as usual (BAU) trends as well as more transformative scenarios. Finally, we bring these different lines of evidence together, along with previous research on structural land use transitions, to synthesize general conclusions about global land use dynamics. Throughout, we report areas in Mha, which is not a standard SI unit, because the orders of magnitudes of most changes are more readable that way, and because many previous studies use these units.

2. Recent trends of land use area and intensity change

Various forms of land use and management cover somewhere between 64% and up to 76% of the Earth's ~13100 Mha ice-free land surface, in the reference period around 2015-2020 (9–12). This includes ~4710-4800 Mha of grazing land (~36% of the ice-free land surface), of which ~1480 Mha of intensive grazing and the rest being less intensive grazing; ~1990-2810 Mha of forestry (15-22%), gathering a range from intensive plantations to other planted forests, and natural forests used at various intensities ; ~1570-1590 Mha of cropland (12%), including crops directly consumed by humans and crops for livestock feed, biofuels and other industrial products; and ~140-160 Mha of infrastructures and artificialized land, including settlements and other built-up area, and mining (covering 7-15 Mha, (13–15)). Infrastructures represent only ~1% of global land, but are highly influential on land use dynamics (2). Agricultural lands (grazing land and cropland) occupy almost half of the ice-free surface, of which about 80% is used for livestock. Vegetated land

without direct and discernible land use influence accounts for 2140-2600 Mha (~12 to 20%) of the ice-free land area, primarily in remote tropical and boreal regions, and the remaining 1560-2100 Mha are unproductive deserts, barren or snow-covered land.

Large uncertainties remain on the overall extent of certain land uses, as the boundaries at the extensive margin remain unclear (forests only lightly used for timber harvesting, or grasslands used for infrequent, seasonal and extensive grazing). In contrast, directions and rates of change in these land uses are somewhat more firmly identified¹ (Figure 1). We focus here on trends over the 21st century, other works present global land use trends over longer time spans (17). We do not review here the environmental implications of these trends, this has been done elsewhere (e.g., (17–19) and many others).

< INSERT FIGURE 1 HERE >

2.1. Natural forests and non-forest natural ecosystems

The dominant trend in natural ecosystems is decline, through conversion to different land uses, mainly agriculture. Total tree cover loss for the representative year 2018 amounted to ~27.73 Mha (+2.20 Mha) (20), yet, much of that is rotation in forestry operations or shifting cultivation cycles. From that area, an estimated ~8.04 Mha (+1.01 Mha) were forests converted towards other land uses (mainly pasture, 52%, and cropland, 25%). Much of that is concentrated in tropical regions (between

¹ This contrast between large uncertainties in overall areas versus more consistent evidence on changes has been well shown and discussed, e.g. for forests and deforestation by Grainger (16).

6.5-9.5 Mha/y (21) and ~ 7.00 (± 0.98) Mha/y (20)), and even more, in specific frontier areas (22, 23).

Dynamics of forest recovery have been increasingly documented. Yet, globally, reforestation remains much smaller than deforestation. From (24) we estimate that probably less than 4.7 Mha/y have experienced lasting natural tree cover gain between 2000 and 2010, outside of regions where most gains are associated with tree cover loss and burned areas (and are thus presumably regeneration from either logging or disturbance). The FAO Forest Resources Assessment data (25) identify 32 countries with sustained expansion of natural forests over 1990-2025 ($>+1\%$, and at least 100,000 ha of natural forest in the country), accounting for a total of ~ 1.91 Mha/y of natural forest expansion, or ~ 1.87 Mha/y over 2010-2025 (including countries like Russia, China, India, with large internal heterogeneity in trends).

Non-forests ecosystems are also being converted, with an estimate of ~ 8.65 - 12.15 Mha/y of grasslands, shrublands and wetlands being converted towards cultivated land over 2000-2020 (26). This is thus an even higher rate than forest ecosystems, and which has accelerated over 2010-2020 compared to 2000-2010.

2.2. Agricultural land uses

Cropland

Trends in cropland area, including here arable land and permanent crops such as tree crops, show a continuing expansion, with annual increase rates appearing to accelerate over the recent decades: according to FAO, from $+2.40$ and $+2.05$ Mha/y respectively over 1984-1994 and 1994-2004 to $+4.65$ and $+3.58$ Mha/y over 2004-2014 and 2014-2024 (27). Independent estimates from Earth Observation (EO)

similarly indicate an acceleration of cropland expansion (here excluding tree crops and shifting cultivation), with on average $\sim +6.4$ Mha/y (95% confidence interval: ± 2.8 Mha/y) over 2003-2019, but with a near doubling of the annual expansion rate over the course of the last two decades (28). This is presumably an underestimation, as cropland remains poorly mapped in certain regions that have rapid expansion, such as in Sub-Saharan Africa (29, 30).

Regarding trends in intensity, since 1961, aggregate global crop yields growth, in calories, has been linear, at around $+100$ Kcal/ha/year, with no detectable acceleration or deceleration over the recent decades (31). Caloric yields increased from 4330 Kcal/ha in 1961 to ~ 11000 Kcal/ha in 2021, i.e. $+158\%$. This aggregate trend hides vast regional disparities, with about a third of the global rice, wheat and maize production occurring in regions that have recently experienced no yield gains, stagnation or decline (32, 33). Most (94%) of the increase in crop production over the recent years has been coming from intensification, rather than from cropland expansion (6%) (34).

Pasture, grazing lands and livestock

Trends in pasture area have larger uncertainties than for cropland. FAO indicates a contraction of pastures globally over the recent decades, with annual rates going from $+5.37$ over 1984-1994 to -4.83 , -6.61 and -9.15 Mha/y over 1994-2004, 2004-2014 and 2014-2024, respectively (27). Yet no robust independent EO estimate can cross-check these numbers. Evidence from Global Pasture Watch indicate that a gross ~ 2.81 Mha/y of cultivated grasslands have been converted to cropland, and in total cultivated grasslands saw a net contraction of 2.22 Mha/y between 2015 and 2024, and that, but what is identified as “cultivated grasslands” is

only a small portion of total global pastures (35, 36). This net loss results from a combination of much larger gross loss of pasture, mostly in temperate regions, and gross expansion mainly in tropical regions. Over 1999-2023, reduction of livestock density has been occurring mostly on land already used extensively, including in Asian Russia, North America, or arid regions in Northern and Southern Africa, or Oceania (37). This suggests that the global pasture contraction recorded corresponds mainly to situations where gradual decline of extensive grazing leads to land being eventually recorded as not used for pasture anymore. These may bring both positive and negative social and environmental consequences, but such marginal changes in extensively grazed areas can hardly be interpreted as a clear sign of the reduction of human pressure on nature.

Overall, global livestock production has intensified steadily over the second part of the 20th century, with ~30% increase in carcass weights per animal for chicken and beef over 1961-2008, and ~20% for pigs, and similar increases of milk yield per cow and eggs per chicken (38). Intensification also manifests itself in land use, with an estimated reduction of 62% land requirements to produce one kilocalorie from livestock around 2015 compared to 1961, through gradual shifts from pasture-based towards more cropland and feed-based livestock, and from ruminants to more intensive pig and poultry production (17). Despite this intensification trend, animal products, including meat, aquaculture, eggs, and dairy use, have been estimated to require ~83% of the world's farmland (39). As for crop yields, global trends hide important regional concerns, with ~27% of the global grazing lands experiencing a decrease in livestock carrying capacity, measured as grass primary production over 2001–2015, mostly in Europe and southeastern Brazil, against 15% seeing an increase (40).

Overall agriculture

Trends in agriculture overall are essentially the combination of trends in cropland and in pasture. Overall trends in agricultural productivity can also be assessed through changes in Total Factor Productivity (TFP), i.e., the ratio between overall economic outputs and overall economic inputs of farm production (18, 41). TFP growth has been ranging between 0.5-2.5%/y across world's regions, accompanied also by a decline in emission intensities, which was proportionally larger than TFP growth in all regions except high-income Asia.

2.3. Forestry

Trends in forestry areas are recorded by the FAO Forest Resources Assessment, but this reports on designated purposes (e.g. forest designated to production) or status (naturally regenerating forests, which might thus have been logged more or less recently), not the area actually affected by forestry activities. Overall, the extent of forest areas dedicated to production has been fluctuating over the recent decades, with a negative trend of -2.24 Mha/y over 2005-2015 being replaced by a positive trend of +1.97 Mha/y over 2015-2025 (25). When adding forests dedicated to multiple use, the trend is negative over 2015-2025, at -6.02 Mha/y. EO studies identified ~7.25 (+- 1.66) Mha/y of tree clearings related to forestry activities (20), but the trend is unknown. Trends in all naturally regenerating forests are clearly negative, with -11.63 Mha/y over 2005-2015 and -6.97 Mha/y over 2015-2025, yet, these forests include forests that are part of shifting cultivation cycles or regenerating after natural disturbances, and forestry areas, this trend is thus not indicative of how

the footprint of logging is changing over time. Forests are thus contracting overall, but within that, the area specifically dedicated to forestry production increases.

Planted forests, of which most, but not all, are designated for production, have been steadily expanding, albeit at a decelerating rate, from 6.05 Mha/y over 2005-2015 to 2.82 Mha/y over 2015-2025 (25). About half were plantation forests, i.e. intensive even-aged monocultures, expanding by 3.79 and 1.67 Mha/y over these periods. As a result, the ratio of planted forests over the total area of production or multiple use forests has slightly increased over time, from 0.10 in 1990 to 0.14 in 2010 and 0.17 in 2025, suggesting an intensification trend (25). Beyond these ratios, trends in global forestry intensity are very poorly measured. The global consumption of primary processed wood products has increased from 1.8 billion m³ RWE3 to 2.3 billion m³ RWE from 1990-2020. Put in relation with the area of forest designated for production or multiple use, it also suggests an intensification trend from 0.94 RWE m³/ha in 1990 to 1.22 RWE m³/ha in 2020, or +31%, presumably due in notable, but unknown, part to the expansion of plantations, and perhaps their increase in productivity. But there is no comprehensive and robust dataset on global trends of productivity within planted forests themselves². One assessment reported that in 2012, 46.1% of total industrial roundwood production was coming from planted forests (42), but there is no temporal assessment of this, only modelling studies.

² Some works provide estimates from field trials, but there is no way to derive upscaled figures from these. Some works provide estimates of roundwood volumes obtained from planted forests, from which figures of wood productivity per hectare of planted forests could be calculated, but this would be circular as these works themselves build their calculations of planted forests roundwood volumes on estimates and assumptions about productivity.

2.4. Artificialized areas: Built-up, urban, settlements, impervious areas, and mining

The GHSL/WUP data indicate rates of built-up area expansion of +0.77 Mha/y over 2005-2015 and +0.93 Mha/y over 2015-2025 (43, 44). Over the longer period 1985-2015, estimates differ, with the World Settlement Layer - Evolution dataset reporting higher rates of settlement expansion of +1.97 Mha/y (45), and the global annual urban dynamics (GAUD) reporting urban expansion of +0.97 Mha/y (46). An average of four global products on impervious surface area showed expansion rates of $+1.59 \pm 0.33$ Mha/y over 1993–2018 (47). Some datasets focus primarily on built-up area, with lower figures, while other datasets cover impervious surfaces more broadly. Beyond built-up and impervious surfaces, mining areas represent another form of severe disturbance, generally removing vegetation and top soil. Mining expansion has fluctuated between +0.14-0.19 Mha/y over 2011-2022 (48).

These trends show extensification, not intensification, as the built-up area per capita has been increasing globally and in all regions over the last decades, from an average of 161 m² per person in 1990 to 169 m² per person in 2020 (49). Rates of urban land expansion have remained above rates of population growth with a ratio fluctuating between 1.01-1.16 over 2000-2020 (i.e., 1% increase in population leads to a 1.01-1.16% urban expansion), and even a sudden jump to 2.62 over 2020-2025 (50).

2.5. Key insights from recent land use dynamics

First, overall, rates of forest conversion remain notably above the rate of natural forest regrowth, and conversion of non-forest ecosystems has been even larger and

accelerating compared to deforestation. Although a number of countries appear to have experienced a forest transition (i.e., structural shift from net deforestation to net forest expansion, (6) and see Section 2.1), there is no indication of any global turnaround in forest cover, and even less for non-forest ecosystems.

Second, on the one hand, regional slowing down or declining trends in cropland or grazing land productivity appear to have not yet, so far, led to a global productivity decline, being compensated by regions with increasing trends, although this entails concerns about unequal development and food accessibility.

Third, some of the numbers here are gross changes, i.e., deforestation, and non-forest ecosystem conversion, gross natural forest expansion, and artificialized land expansion. Others, i.e. planted forest expansion, pasture contraction, and cropland expansion, are net changes. These net changes result from much larger gross dynamics, e.g., the net cropland expansion of 6.4 (+2.8) Mha/y results from a gross expansion of 13.6 (+2.4) Mha/y and a gross contraction of 6.7 (+1.5) Mha/y (28). Thus, the area affected by cropland-related changes is over three times larger than the net cropland change figure. The same is true for other land uses, with historical reconstructions suggesting that almost a third (32%) of the global land area has been undergoing land use change over 1960-2019 (51). Even if the area of certain land uses stabilizes at the global level, such as pasture lands, these land uses are still expanding in certain regions, with new frontiers of natural ecosystem conversion, crop booms and other land use changes continuing to emerge and progress across the globe, with large impacts (22, 23, 26, 52, 53).

Fourth, our picture on global land use dynamics and land use transitions remains very imperfect. On the one hand, we have global land cover datasets (36, 54, 55) which can provide time series of transitions, but, beyond well known issues in

assessing transitions from overlaying maps of different time points, these datasets do not adequately map some major land uses such as grazing lands and forests used for timber. Alternatives are modelling reconstructions (11, 12, 51, 56), which are extremely useful as inputs for other studies (e.g. on Earth system dynamics) but do not, in themselves, help shedding light on the unknowns.

Fifth, this being said, using the best available estimates of these different land use dynamics (Figure 1), the “land budget” doesn’t close. More land goes “out” than new land use areas appear. This suggests that either there are detection issues, or that some places live out there in a pool of land that is not recordedly used, or was cleared but not really used for productive purposes, because of a range of reasons including speculation, mismanagement, tenure conflicts, economic drawbacks, and others (21, 57).

3. Land use spillovers

This section reviews the empirical evidence on land use spillovers, including (i) leakage from land use policies and interventions, (ii) some of the major forms of indirect land use change (iLUC) (e.g. commodity crop expansion into smallholder agriculture, soy-pasture interactions in Brazil), (iii) rebound and land sparing effects of intensification, and (iv) agglomeration economies. The theoretical underpinnings and mechanisms of these dynamics have been reviewed elsewhere (7, 58–60), as well as their relevance for achieving sustainability through land use (2, 8), therefore we focus here on key recent contributions, and in particular on empirical evidence about the rates and spatial patterns of these spillovers.

3.1 Leakage and indirect land use change

Regarding the understanding of iLUC, in the context of biofuel policies, a recent study identified five primary mechanisms through which iLUC may be fostered (feed or staple crops substitution, land use displacement), or hindered (biofuel feedstocks substitution, budget constraint, and crowding out), and provide evidence that these mechanisms lead to an overall positive effect on indirect land use change overall, except in tropical Africa where the hindering mechanisms appear to dominate (61).

To assess rates of leakage and indirect land use change reported in the literature, we built on several recent systematic literature reviews and meta-analysis of land use spillovers, including: Fuller et al. (2019) (62) (systematic review of deforestation spillovers from protected areas, compiling data on spillovers from seven studies over 3404 protected areas across the globe); Ford et al. (2020) (63) (study of deforestation leakage in a pan-tropical and subtropical selection of 120 protected areas); Fuller et al. (2020) (64) (study of deforestation spillovers in 91 protected areas in Brazil); Pan et al. (2020) (65) (meta-analysis on carbon leakage in forest sectors); Ramírez-Mejía et al. (2025) (66) (systematic literature review on land use spillovers, focused on causal mechanisms); and Gliottone et al. (2026) (67) (systematic literature review on spillovers from protected areas, focused on methods). We added some studies too recent to have been included in these reviews, or discarded from these due to their respective criteria and foci but relevant for our assessment.

We compiled the studies inventoried in these systematic reviews, and assessed the spillover cases reported (see details in the Supplementary Material). When possible, we calculated the rate of leakage or indirect land use change for each case reported, based on formulas below, and a minimum and maximum rate when uncertainties

were reported. Overall, we assembled a dataset of 2807 individual estimates of leakage or indirect land use change rate.

We used the following formulas:

$$(1) \text{ Leakage rate} = (\text{area of land use change or deforestation due to the leakage} / \text{area of land use change or deforestation avoided within the intervention scope}) \times 100\%$$

Positive rates indicate leakage, while negative rates indicate “blockage”, i.e., the intervention reduced the targeted land use change (e.g., reduced deforestation) outside of the intervention scope area.

$$(2) \text{ Indirect land use change rate} = (\text{area of land use change elsewhere caused by the initial land use change} / \text{area of the initial land use change}) \times 100\%$$

We used a simplified categorisation of interventions to identify major patterns. The amount of data for most interventions (except protected areas) did not allow to distinguish many subcategories or to robustly explore regional, temporal or other patterns. The categories were as follows:

Protected areas (PAs) (n=2735): public areas designated for conservation, including also, in certain studies, indigenous lands or other forms of reserves or conservation areas; further divided in subcategories of cases coming from the three main sources, i.e. (i) Fuller et al. 2019 (n=2575), (ii) Ford et al. 2020 (n=55), (iii) Fuller et al. 2020 (n=91), as these sources have distinct methods for assessing leakage and some have very large datasets, and (iv) all other sources (from (66, 67), and own sources) (n=14).

Forestry (n=37): interventions such as logging bans, moratorias or harvest reductions, REDD+ interventions, as well as reforestation policies, in certain cases

supported by carbon credits schemes; further divided in subcategories of domestic (n=15) versus international (n=22) leakage.

Supply chain (n=15): private-led or public interventions to influence land use change and deforestation through agricultural or forestry commodity supply chains, such as certification schemes, moratoria, zero-deforestation commitments, as well as public interventions such as due diligence regulations; further divided in subcategories of domestic (n=6) versus international (n=9) leakage.

Agricultural policy (n=11): policies targeting agricultural lands directly such as agricultural conservation reserve programs, emissions reductions in agriculture, and others.

Indirect land use change (n=9): mostly cases of biofuels mandates or cascading land uses in South America (sugarcane / soybean / pasture).

These categories are often associated with certain methods and types of leakage. Leakage for PAs is usually assessed using quasi-experimental, causal inference approaches such as matching or difference-in-difference, in buffers of various sizes, focusing on local activity leakage. International leakage in forestry, supply chain interventions and agricultural policies is usually assessed using economic modelling, capturing market leakage, while domestic leakage in these groups corresponds to a mixed bag, including some REDD+ or reforestation projects analyses based on matching & buffers similar to PAs, but also economic modelling similar to international leakage.

< INSERT FIGURE 2 HERE >

The synthesis (Figure 2) leads to six key observations. First, there are much more observations for protected areas (PAs) than any other form of intervention. Unsurprisingly, thus, the distribution for PAs also goes more into the extremes, but this also results from the intervention itself: many PAs have a very low effectiveness, and thus a very small denominator in the calculation of leakage, thus resulting in sometimes very high (positive or negative) figures.

Second, overall, PAs display a very different pattern than other interventions. The median response is blockage (-1.31%), i.e., protected areas also protect their surrounding landscapes, noting that these studies span a large range of buffer distances, mostly some kilometers (5 or 10), but sometimes more (20 and beyond). This suggests that, overall, leakage from most protected areas does not appear to be a severe concern (see (64)), and these can even have positive spillover effects. Yet, a share of PAs show leakage, which can be very important in magnitude. It is thus important to identify what are the conditions and contexts in which such high leakage rates may jeopardize the protected area intervention.

Third, these results on PAs are mostly driven by the very large dataset from (62). The other datasets show somewhat different stories. The data from (64), on PAs in Brazil, show an even stronger trend of blockage (median -80%), i.e., the effect within PAs is almost doubled by the same effect outside. In contrast, the data from (63) show a much higher trend of leakage (+310%), possibly because this study uses more robust quasi-experimental counterfactual approaches, leading to lower deforestation rates in the selected counterfactuals than by comparing PAs with overall buffers. The data from the remaining studies on PAs show a spread pattern, with median trends towards no clear leakage or blockage.

Fourth, in contrast with PAs, leakage rates appear generally higher for the other forms of interventions, i.e. forestry interventions, supply chain interventions, and agricultural policies (median respectively 49.5%, 37.5%, and 20%). In contrast with PAs which are often established in relatively pristine and passively protected places, and aim to prevent potential pressures, the other forms of interventions directly target existing land uses, such as agricultural set asides or reforestation policies, and may focus on commodities with high rent and demand inducing high land use pressures. Targeting already existing land uses (rather than potential ones) or high-demand ones is more likely to create higher leakage, either through activity leakage (land users displaced expand their land uses elsewhere) or market leakage (markets for high demand commodities send signals to producers elsewhere).

Fifth, for supply chain and forestry interventions, international leakage appears higher than domestic leakage (median of respectively 40% versus 13% for supply chain interventions, and 68% versus 4% for forestry). An exception is supply chain interventions in Brazil, which have higher domestic than international leakage, but in the context of a very large country that has ample room for absorbing spillovers domestically (68). This suggests that for large-scale interventions such as moratoria or zero-deforestation commitments, logging bans, or other forestry policies covering large regions within a country, leakage might occur more strongly through market linkages leading to adjustments in exports and imports, which are often reported to cancel about 50% or more of the intervention's effect, than through activity leakage where the land users in the targeted place move to another place domestically.

Sixth, methods presumably influence the results observed. The economic models never predict more than 100% leakage, by design leakage is a fraction of the main effect of the policy, while the buffer analyses can range across orders of magnitude

because estimated leakage in the buffers can be larger than the protection effect in PA (even more if the buffer is larger), and if that effect is small (small denominator) the fraction becomes large (negative or positive). Similarly, the scale of the indirect land-use change process differs - studies based on buffers (e.g., around PAs) capture only local changes, while supply chain studies include global feedbacks.

3.2. Rebound effect and land sparing

Rebound effect is a spillover where increasing productivity of a given land use stimulates its expansion. It opposes land sparing, i.e., reduction of land demand along with intensification (Figure 3). Rebound can be partial, i.e., intensification spares land but proportionally less than the intensification, or complete, leading even to “backfire”, i.e., the intensification induces a net land use expansion (59). Further, land sparing can be absolute, i.e., resulting in net farmland contraction, or relative, i.e., reducing per-capita land demand or the rate of agricultural expansion compared to the counterfactual scenario without intensification (7). Comprehensive analyses of rebound effects in land use have been provided by (59, 69, 70), so we here recap their main findings and then expand on this from the subsequent literature.

At a global level, increases in agricultural productivity, measured through yields or TFP, have resulted in relative land sparing, although with a partial rebound effect. A 1% uniform increase in TFP globally led to a 0.34% reduction in global cropland area (18, 69, 70). Similarly, productivity change linked to a reduction of inputs use by 30% led to a ~10% reduction in CO₂ emissions from agriculture (71).

These global effects resulted from heterogeneous trends across regions and crops. Regarding crops, commodities with high price-elasticity of demand, including rubber, flex crops (sugarcane, oil palm and soybean), and tropical fruits, displayed complete

rebound effect, while the intensification of staple cereals such as wheat and rice resulted in land sparing (59). Land sparing concentrated in temperate, higher income regions, and rebound effects in tropical lowlands of low- to middle-income countries (72). Several studies have thus focused on tropical regions. A study over 2000-2015 in 122 tropical nations found negative cross-sectional association between yields increase and forest area change in Sub-Saharan Africa and Latin America and Caribbean, suggesting a rebound effect, but no effect appeared in a panel analysis (73). Across tropical dry forests and woodlands, agricultural intensification between 2000 and 2020 was generally associated with increasing forest loss, with a 100% increase in yields being associated with an average 3.8% increase in forest loss, especially where agricultural production is predominantly for commodity markets, while indigenous lands exhibited a land sparing effect (74). In Brazil, municipalities with greater exposure to productivity gains from genetically engineered soy lost 1 percentage point more forest compared to areas that did not benefit from the new technology (75). Several local studies showed marked rebounds: In Gambia, development programs supporting agricultural productivity explained one quarter of the total forest loss in studied villages, essentially in remote villages (76). In DRC, access to improved seed did not lead to changes in overall deforestation rates but led to relative increases in primary versus secondary forest clearing, due to the higher nitrogen requirements of improved seeds (77). In contrast, in Uganda, an agricultural intensification program, mostly through labor-demanding forms of intensification, reduced the annual deforestation by 14% (78). Beyond land use area, rebound effects also occur in water use for agriculture with improved irrigation systems (79) and in consumption rebounds with interventions to reduce food loss and wastes (80).

< INSERT FIGURE 3 HERE >

3.3. Agglomeration economies

Agglomeration economies are another spillover that remains understudied in land use (81). Studies in Brazil showed that spatial clustering of soy producers was favoring increases in productivity (82). In Mato Grosso, economic effects of soy spatial agglomeration are estimated to increase by 5% the probability that a plot is converted to cropland, when 40–50% of a neighboring area was already used for cropland (83). The non-linear observed effect in that study corresponds to theoretical predictions and evidence from investors interviews that these actors seek a balance between benefiting from agglomeration economies and looking for cheap abundant resources in frontier conditions (81).

4. Global land use change: Emerging drivers and prospects

4.1 Emerging drivers of land use dynamics

Many works have analysed local drivers of land use change, as well as slow-changing structural drivers such as demographic, economic or technological change, including changes in population density, GDP per capita and consumption, urbanization, technologies and Total Factor Productivity (TFP) in agriculture (17, 18, 84), as well as distal processes such as domestic and international trade, e.g., (85–87). Here, we highlight four societal trends which have not yet been well or fully

incorporated into land use projections, and might shift the trends in very distinct directions.

First, the changing political context, internationally and domestically in many countries, adds to the challenges of achieving sustainable land uses. The interactions between a geopolitical context where multilateralism is in decline on the one hand, and the increasing pressures on natural resources on the other hand mean that land and its resources are increasingly a subject of geopolitical plays, from trade wars impacting agriculture to conflicts and race for critical minerals (88–90). Further, a widespread trend of democratic backsliding, authoritarianism and populism also interact with land use (89, 91, 92). The relations between the multiple processes of democratic backsliding and land use and sustainability operate through ideologies, worldviews and values about land and land use, as well as through concrete decisions and policies (or policy dismantling and deregulation), though with still unclear impacts. Land use dynamics might themselves affect democratic backsliding through feedback loops, as land degradation, inequitable sustainability interventions, or even the land use outcomes of authoritarian or populist regimes put increasing pressure on land users and societies (91).

Second, the power and nature of economic actors are also changing. The largest agrifood corporations are increasingly concentrating larger shares of major agricultural markets (in products, as well as in inputs such as seeds and agrochemical inputs) (93, 94). Such corporate concentration means that a few key actors can exercise market power and earn excess profit, shape the structure and functioning of food systems, and influence the politics, policy and governance processes of food and thereby land use (95). Further, not only the market dominance, but also the nature of these actors has been changing, as the agri-food

and land use sectors have been experiencing an increasing role of financial motives, markets, actors and institutions. This financialization manifests as opening new modes of capital accumulation, an increasing prioritization of shareholders' returns in corporate decision making, and a complexification and embedding of financial activities into the functioning of the sector (96, 97). Financialization has been mainly described in the agri-food system, but is also prevalent in other land use sectors such as forestry (97). This concentration and financialization increases inequalities and drives food and land systems towards specific trajectories of industrial, intensive, high capital and input-dependent land uses, hindering environmental governance (98). Concentration at the farm level also strongly affects the number of jobs that farming and other land uses can provide (99, 100), which matters especially in a context where many countries in particular in Africa and Latin America have little prospects for industrialization opportunities, and populations going out of farming are trapped into low-productivity jobs (99, 101). Financialization leads to land being increasingly treated as a financial indicator rather than a productive asset (102), which suggests that land use decisions might increasingly reflect trends in financial markets and speculation (57). Recent empirical mixed-methods works revealed a vast diversity of goals, strategies and decision-making logics of investors and other corporate actors, with network and herd effects leading to surges of investments that may be hard to predict (81, 103, 104). Other works aim to identify how concentration can be leveraged to drive systemic changes by focusing on a few “keystone” actors (105), such as major commodity traders (106).

Third, despite setbacks and backlashes, ambitious sustainability agendas and efforts are increasingly assigning additional purposes and functions on land, which may compete with other land uses such as for food, timber or settlements. These include

conservation, which, as long as it is an assigned function to land accompanied by the corresponding management, behaves as other land uses (107); afforestation or reforestation done with a focus on rapid carbon storage, often through fast-growing tree plantations; renewable electricity production through solar panels, windmills, and hydropower infrastructure; bioenergy production through either wood production (wood pellets), flex crops such as oilseeds (soy, oil palm) or ethanol crops (sugarcane, maize); expansion of mining for critical minerals or energy-transition minerals (ETMs); as well as multiple nature-based solutions such as areas assigned for hydrological flows regulation or local weather regulation, or recreation, educational, and cultural purposes, which may overlap with conservation areas (9, 108). Multilateral agendas such as the Global Biodiversity Framework include not only conservation but also ambitious restoration commitments, including forms of rewilding (109), with vocal actors putting forward visions of nature as not a passive or residual category, but as a competitive use of the land that actively takes its space against others (110, 111). Other calls for reconciling human needs and societal justice with environmental sustainability in land uses build on agroecological, organic and other farming approaches. Prospective approaches have started to explore global and regional land use scenarios along these lines, e.g., a recent study showed that the ambitious policy targets of the European Union of 25% organic farming could be achieved without outsourcing land use and related emissions, if accompanied by adequate but realistic changes in diets (112), and some works have started to explore degrowth or post-growth scenarios to enhance sustainability through land use (113, 114). Other works have been exploring Controlled Environment Agriculture (CEA) (e.g., vertical farms), suggesting that over 420 Mha of targeted crop production, these approaches could save ~107 or up to 145 Mha in

the optimistic upper bound scenario (115), although detailed life cycle analyses suggest that the actual land-saving outcomes of these approaches depend on multiple parameters such as the energy source or origin of the substrate (116).

Fourth, environmental changes, including land degradation and impacts of climate change, increasingly affect land use and land cover, not only indirectly, such as by affecting the productivity of agriculture through droughts or soil degradation, or affecting workers' health, but also directly, in particular through fires. Global area burned has been declining, by -27% over 2001-2019 (117), essentially due to expansion and intensification of agriculture (118), including in grazing lands (119) and areas under smallholder and subsistence farming (120). Yet, this global decline is essentially driven by trends in grasslands and savannas regions, essentially in Africa, while no such decline occurred over forest areas globally (117). Multiple lines of evidence indicate an increase in wildfires in some key forest regions such as Amazonia, boreal forests, or North America's Pacific forests (117). The frequency and extremity of fire-prone weather has also been increasing in most regions over 1979-2019 (117). Fires directly impact agricultural and urban land uses, as well as afforestation and reforestation efforts made for climate change mitigation and nature restoration (121). Fire risk also influences land use by driving land use regulations, such as land zoning for urban development (122). Projections forecast continuing trends of increases in the prevalence of fire-prone weather (117, 123), but the trends in burned areas remain very uncertain, depending on complex interactions between climatic, biotic and anthropogenic drivers (124). Beyond uncertainties on the prevalence of fires, interactions between environmental change and land use complicate the attribution of impacts of fires such as CO₂ emissions (125), and thus

the governance of land use dynamics, e.g., by complicating the impact evaluation of interventions.

4.2 Prospective land use trends

Here, we compiled data on forecasted global rates of major land use changes over the period 2020-2050. This section builds on the recent assessment by (9), which compiled business as usual (BAU) trends of major land uses, as well as the area implications of public commitments towards key land-impacting sustainability interventions, as well as several other key studies.

Baseline or Business As Usual trends

The baseline or BAU trends compiled here correspond to projections based on continuation of current drivers trends, including current trends in changing demography, income, diets, productivity, etc, and the implementation of current sustainability policies. These are thus not necessarily continuations of current land use trends (if the trends of the underlying drivers lead to changing land use dynamics), and these also are not trends without policy interventions.

Compared to the assessment by (9), our BAU here includes more estimates in particular from (126), and we focus on the median (and Q1-Q3) of the estimates. These result in projected land use expansions of 3.31 (1.83 - 5.81) Mha/y for cropland, -1.99 (-6.96 - +0.36) Mha/y for grazing lands, 1.66 (1.20 - 2.55) Mha/y for built-up land, and 2.02 (1.70 - 3.17) Mha/y for forestry (Figure 4). The larger uncertainties are on grazing land area projections (9).

Alternative scenarios

These projections reveal several key insights. Overall, most scenarios project a continuing expansion of cropland, with the median expansion being 3.04 Mha/y across all projections (BAU and others), and even the sustainability-oriented scenarios projecting a median expansion of 0.73 Mha/y. In contrast, grazing land is expected to continue to contract, but with a very large range of possible dynamics (median of -2.33 Mha/y across all projections, and first (Q1) and third (Q3) quartiles, going from -9.88 Mha/y to +1.25 Mha/y).

Combining cropland and grazing land, scenarios suggest that strong sustainability efforts might lead to an important contraction of agricultural land of a median of -11.3 Mha/y, but even a number of these scenarios result in continuing expansion (Q3: +2.33 Mha/y). In contrast, scenarios that explore less optimistic, but also possible trends in human and environmental drivers show that expansion of both cropland (median: +4.18 Mha/y) and grazing lands (median: +1.34 Mha/y) are still possible.

These studies converge on identifying key drivers that influence the trends including population, consumption patterns and diets, wastes, production systems, trade, and land use regulations. Yet, many aspects remain poorly simulated, such as labor and its interlinkages with the rest of the economy. Most of these studies have been performed using one or several of a few key Integrated Assessment Models (IAMs), including IMAGE, MagPie, GLOBIOM, and a few others. The value of these models is to endogenize at least certain feedbacks internal to the simulated sectors, e.g. between demand, prices, and inputs use in the production, or between domestic production and international trade. Yet, other approaches can provide valuable complementary perspectives, e.g., the rule-based simulation model used in the Agrimonde-Terra prospective exercise was incorporating less feedbacks than typical

IAMs (e.g., international trade is a residual for meeting domestic demand after domestic production is maximized under constraints), but the project developed very thick scenarios in a modular process combining multiple specific scenarios on seven main components affecting land use dynamics (global context, climate change, food diets, urban-rural relationships, farm structures, and livestock and cropping systems), allowing for very rich explorations of possible futures (127).

In contrast with agriculture, less studies have explored trends of other land uses, although their dynamics are of the same order of magnitude as those of cropland and grazing land, and their impacts might be comparable or larger. Room for manoeuvre on forestry and urban areas appear thinner or less explored than for agriculture. Scenarios to reduce the need for planted forest expansion bet on large increases in planted forest productivity or in use of wood residues (128). A major review of urban land-change projections showed that local studies that inform global projections are mostly restricted to a few countries and to large cities, and entail large uncertainties (129). Regions with the highest urbanization rates, such as Sub-Saharan Africa and Central and South America, and small or mid-sized cities, remain under-researched, suggesting that the rates of urban expansion might be underestimated. Conversely, these scenarios do not account for urban shrinkage that might occur in some areas as well (129). The main variable that influences urban land expansion is built-up area per capita, which has been increasing over the recent periods (Section 2). Key parameters for policy interventions to reduce urban land expansion are thus the density of buildings and their verticality, although increasing these while also increasing nature-based solutions in urban areas (green spaces, trees,...) is a challenge for urban planners.

On top of this, several land-based interventions under the global sustainability agenda are also expected to expand (9). Studies project a large expansion of renewable energy generation facilities in order to achieve the commitments to substitute for fossil fuels and mitigate climate change (9, 108), with rates that supersede cropland expansion rates, i.e., median (Q1-Q3) rates of +9.02 (5.94-14.7) Mha/y. This is compounded by expansion of mining for energy transition minerals (ETMs) at rates around +4.53 Mha/y, also larger than forecasted cropland expansion rates. Bioenergy and carbon afforestation trends largely depend on renewable energy and consumption trends, as in most scenarios bioenergy is essentially used as a residual for unmatched energy demand. In what is presented as a land-sparing scenario by the International Energy Agency (IEA), conventional and dedicated lignocellulosic (2nd generation) bioenergy crops would expand by 2.17 Mha/y (9) (in our compilation, the median is 2.98 Mha/y). Achieving current pledges of afforestation and reforestation for land-based carbon removals would require an expansion of 15.23 Mha/y.

Yet, the most striking is that, to achieve public commitments made in particular under the UN-CBD Global Biodiversity Framework (GBF), conservation areas have to expand ~65.8 Mha/y, an order of magnitude faster than any other land use dynamic. Achieving this would require a massive effort to not only reach but also sustain these rates over thirty years, and to manage high impacts on other land uses (111, 130).

Overall, in the assessment of (9), accounting also for other uses such as bioenergy production in forests (270 Mha), the total area of land use demands in 2050 would reach 14240 (13610 - 15520) Mha or ~109% of the overall global terrestrial ice-free land.

< INSERT FIGURE 4 HERE >

5. Insights for global land use transitions towards sustainability

Multiple studies have proposed frameworks and approaches for developing and assessing visions and pathways towards more sustainable and equitable societies and human-nature relations (131). Here, we are not adding on this, but we are distilling a few general conclusions from the previous sections and from previous research on land use transitions, to provide guidance for future transformative transitions of land systems towards sustainability.

Research on large-scale, structural land use transitions identified some key general patterns of land use dynamics. Past agricultural transitions show that societies have often solved certain socio-economic or environmental problems through societal or technological changes that, in turn, have led to new socio-environmental problems (132, 133). Similarly, dynamics of land use frontiers and crop booms-and-busts show that most places do not simply go through a linear sequence of predictable land use transitions from natural ecosystems to extensive and then intensive, consolidated land uses (52, 134). Instead, places often alternate between sequences of more gradual changes in land use and their intensity, and sequences of rapid frontier dynamics when a new resource that can be extracted from land is identified or a new land use spreads into a certain region. Evidence from forest transitions and land abandonment also showed that although such transitions were corresponding to structural transformations of social-ecological systems, the outcomes are not necessarily permanent, reversals may occur, abandoned land can be re-utilized later on, and forest transitions can be followed by important continuing changes in ecosystems such as between natural and planted forests (6, 135–138). These land

use transitions are also characterized by equifinality, i.e., different pathways can lead to similar land use outcomes, and multifinality, i.e., contextual shifts and interactions can lead to divergent outcomes from apparently comparable situations. Land use transitions are often not teleological, i.e., these processes are typically not guided by actors who clearly envision the ending point as a target and drive towards it in a predictable way, but rather by navigating at sight and progressively adjusting decisions along the way.

From this and the previous sections, we can derive some key conclusions about global land use trends and prospects. First, conversion of forests and other natural ecosystems continues at alarming rates, while peak pasture or peak agricultural land remains elusive and is insufficient to reduce global land use pressure. Conversion of non-forest ecosystems is even larger than deforestation, and accelerating, and requires a stronger emphasis in scientific, policy, and societal attention. Works have promoted the idea of humanity having possibly reached “peak agricultural land” globally (34), but this remains highly speculative. On the one hand, very large uncertainties surround pasture lands. On the other hand, with accelerating and likely underestimated cropland expansion, reports of peak cropland (139) have been greatly exaggerated. The small (6%) contribution of cropland expansion to global food production increase has been put forward as a sign that we are approaching peak cropland expansion (34), but, the implication of this number, instead, is that cropland expansion is not crucially necessary for global food production increases, but it doesn’t mean that cropland expansion will not happen. “Peak” would indicate that we have discernable trend of contraction. Instead, a form of plateauing can indeed be observed in overall agricultural land, but BAU projections remain on the fence for the future.

Grazing contraction is a reality in certain regions, but mostly occurs at the (very) extensive margins, where the distinction between land recorded as pasture and that recorded as unused is anyway thin. Further, what is often bundled under the term agricultural land “abandonment” comprises a vast diversity of land use processes and trajectories, with extensification, transient cessation of cultivation and then recultivation, or longer term abandonment (140). Across 11 case studies globally, the average abandonment time of a cropland plot was 14 years, and 38% of the plots that were abandoned at least once between 1987 and 2017 had been recultivated by 2017 (141). The possible ecosystem recovery in these lands is thus often transient. A likely notable, but not well quantified, pool of land has an uncertain status, appearing to have been converted from natural ecosystems, or corresponding to contraction of pasture or perhaps other land uses, but with unclear fate.

This leads to the second point: Gross changes are much larger than aggregate trends, and generally matter more, as environmental and social impacts of land use changes can be very hard to reverse (2). Returning to the premises of this article, even if we focus here on global trends, most impacts depend on a myriad of distributed land use changes. Focusing on targets or boundaries about net global land use areas misses that point.

Third, past evidence and projections point to a need to govern both supply and demand in order to enhance sustainability through land use. Scenarios consistently identify that technological progress alone is insufficient to reduce pressure on land, and that diets and consumption changes are needed. Reducing overall consumption cannot be done equitably without strong efforts from the societies that directly or indirectly consume large amounts of land, in order to allow for everyone to meet their needs. Linear rates of crop yields growth suggest, on the one hand, that, globally at

least, human societies have been able to maintain a steady rate of intensification, and so levelling off of productivity gains have been compensated by more gains elsewhere. On the other hand, this also shows that over eight decades with massive improvements in agricultural technologies, genetics, inputs use, through large-scale transformations such as the Green Revolution, we have been bound to a linear increase, suggesting that any claims from scenario or prospective exercises to achieve higher growth rates, such as through disruptive technological breakthroughs, has a high bar of burden of proof. Globally, intensification has resulted in partial land sparing and partial rebound effect, but in some places, it leads to backfires, inducing gross changes with more rapid consequences than the recovery in other places. Evidence also indicates that the more land use is globalized and integrated, such as through international trade, the larger the spillovers are.

Fourth, more deeply, this review and research on land use transitions suggest that it is unlikely that humanity would achieve a definitive transition towards stable, sustainable land uses. Solutions to certain problems might displace them elsewhere, or create new unanticipated ones. Tradeoffs between intensification and extensification continue to challenge definitive solutions. The best we can hope is probably more or less temporary dynamic equilibriums where the most pressing sustainability challenges are overcome for some time before others appear.

Fifth, indeed, new land use demands and pressures continue to emerge. Grazing lands are replaced by intensive livestock systems requiring more cropland. Urban areas have been extensifying, land is increasingly used for renewable energy production, including mining the related minerals, with expansion rates that would supersede cropland expansion rates if decarbonization commitments are met. Conservation and restoration are increasingly pushed not as a passive or residual

category, but as a competitive use of the land that actively takes its space against others, including high-demand commodity crops, with thus possibly higher risks of leakage to manage. The total land use footprint of humanity is thus still expanding.

Conclusion

Looking at the trends and prospects of global land use dynamics offers a high-level perspective on challenges to enhance the overall sustainability of social-ecological systems through land use. The evidence suggests that globally, conversion of natural ecosystems remains rapid, gross changes and spillovers continue to redistribute even land uses that appear to be globally stable or slightly contracting such as grazing land, and built up, renewable energy production and mining are emerging as major pressures for the coming decades. Meanwhile, ambitious conservation and restoration commitments also create active pressures on other land uses. Balancing these multiple competing demands for land requires transformative approaches that focus not only on land uses themselves but also on moving towards sufficient and equitable societal demands.

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Terms and Definitions list

Definitions to be placed along Section 1:

Land cover: The physical cover and properties of the surface, in particular, the vegetation cover or presence of artificial structures.

Land use: The purposes, functions, and activities assigned to and undertaken on the land.

Land use change: In a narrow sense, conversion from one land use to another. In a larger sense, it includes land management changes.

Land management change: Changes in the activities, including intensity, within a given land use, without conversion to another land use.

Land systems: Terrestrial social-ecological systems where human and environmental systems interact through land use.

Land use transition: Either a transition from one land use to another, e.g., pasture to cropland (142), or large-scale, structural or systemic transitions from one land use system or regime to another (4–6).

Land use spillovers: Processes by which land-use changes or land use interventions (policy, technology) in one place have impacts on land use elsewhere (7, 60).

Definitions to be placed along Section 3:

Land use leakage: Spillover caused by an environmental policy, which reduces the overall effectiveness of this intervention (60).

Indirect land use change (iLUC): Spillover where land use change in one place is caused by land use change in another place (60).

Activity leakage: Leakage when land users, and their assets (labor, capital) used on the land targeted by restrictions move to other, in general somewhat local, places with available and accessible land.

Market leakage: Leakage in which land use restrictions induce changes in product prices and land use expands elsewhere in response to these changing market conditions.

Definitions to be placed along Section 3.3:

Agglomeration economies: Economies of scale that are external to the individual agent or firm (81).

Figures

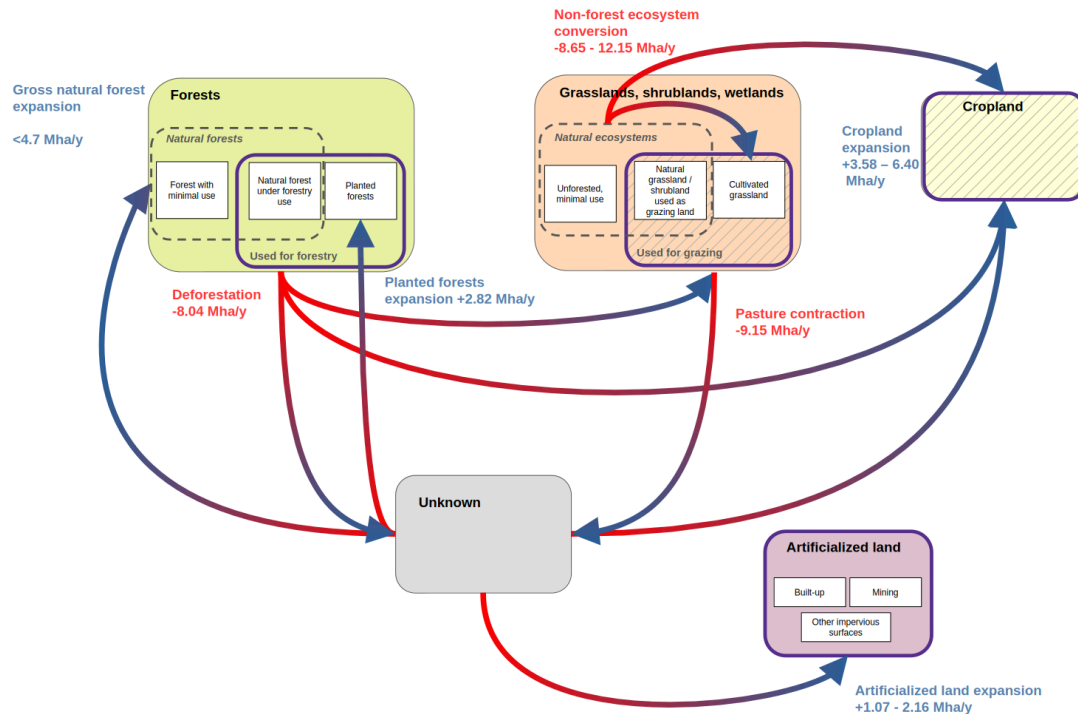


Figure 1. Major global land use dynamics. Numbers present the best estimates of land use change rates, over the most recent period available (see text). Blue text indicates data about expansion (inflows), red indicates data about contraction (outflows). Thick indigo outlines identify main land uses. Dashed areas are agricultural lands. The size of the boxes and the arrows does not reflect the size of the areas or flows. The 8.65-12.15 Mha/y of non-forest ecosystem conversion and the -9.15 Mha/y of pasture contraction are entangled, as (i) the former includes some natural grazing lands being converted to other uses, or being converted to cultivated grasslands, and (ii) the latter number includes natural grasslands previously used for grazing and taken out of use. Sources: See text and Supplementary Material.

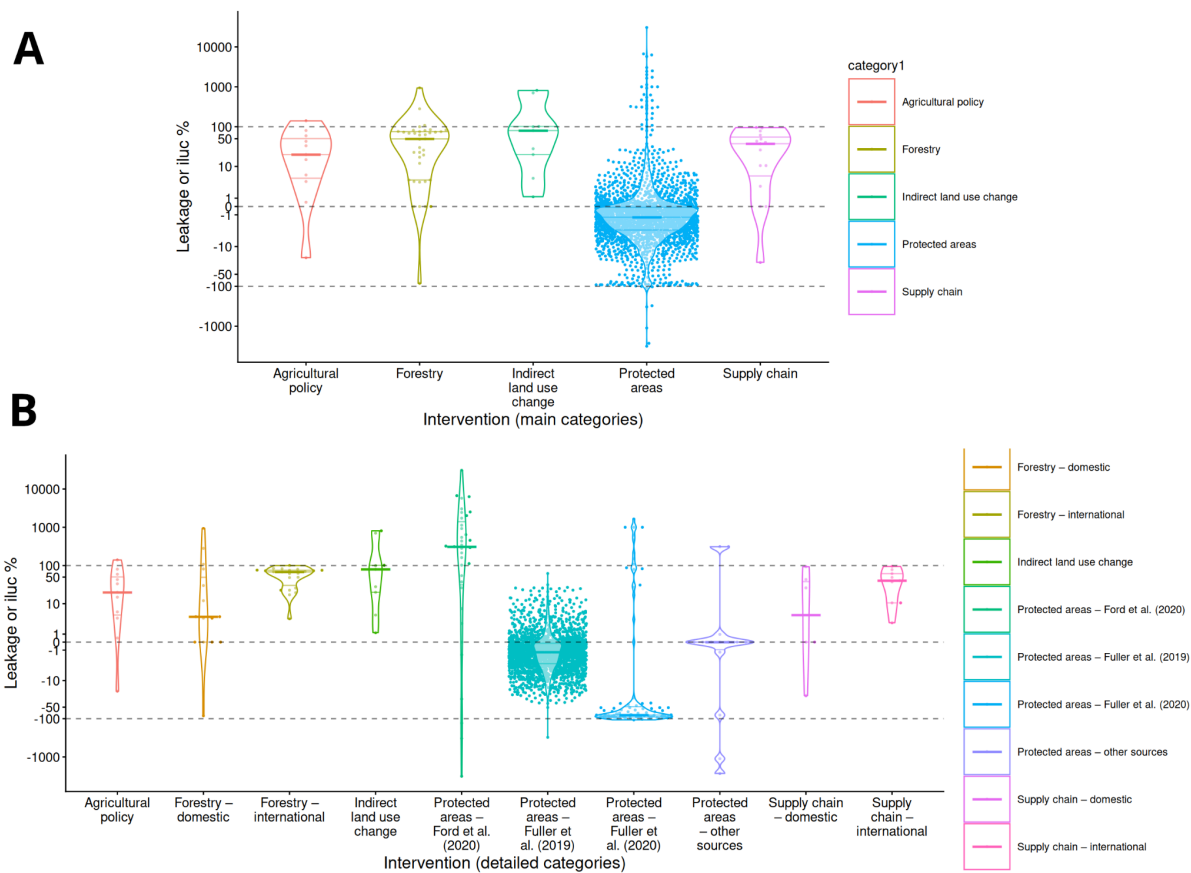


Figure 2. Estimates of rates of leakage and indirect land use change. A. Estimates grouped per broad categories of processes. B. Estimates per subcategories of processes. The graphs present a beeswarm representation of the individual estimates (dots), violin plots of the distribution, and quartiles (first and third quartile: thin horizontal line, second quartile (median): thick horizontal line). The numbers are compiled in Table S1 and S2.

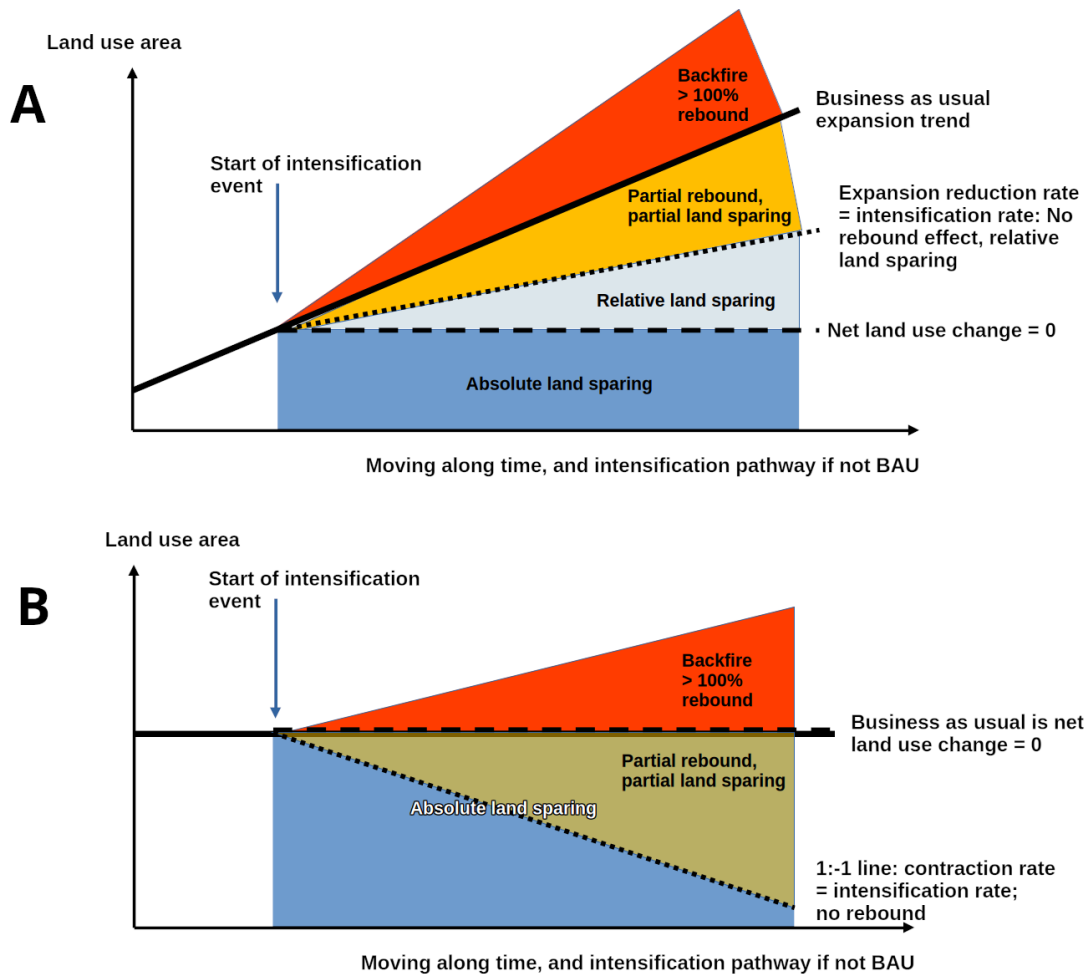


Figure 3. Different categories of rebound effect and land sparing as a result of intensification.

A. When the baseline trend of the given land use is towards expansion. Absolute land sparing corresponds to a shift to contraction of that land use. Relative land sparing occurs when the expansion rate is reduced due to intensification but remains positive. When the expansion is reduced at the same rate as the intensification (i.e., the trend of overall production remains unchanged as productivity gains compensate for a reduction of expansion), there is no rebound effect. When the expansion is reduced but proportionally less than the intensification rate (so that the overall production increases more than the baseline rate), there is a partial land sparing and a partial rebound effect. If intensification results in an acceleration of the expansion, i.e., production increases both because of expansion and intensification, this is a backfire effect. B. When the baseline trend is that the land use area is stable. As in A., absolute land sparing corresponds to a shift to contraction of that land use. When the contraction rate is lower than the intensification rate, there is a partial land sparing but also a partial rebound effect. Backfire occurs if intensification leads to an expansion of that land use. There is no situation of relative land sparing in this configuration. Based on (7, 59, 143) and works cited therein.

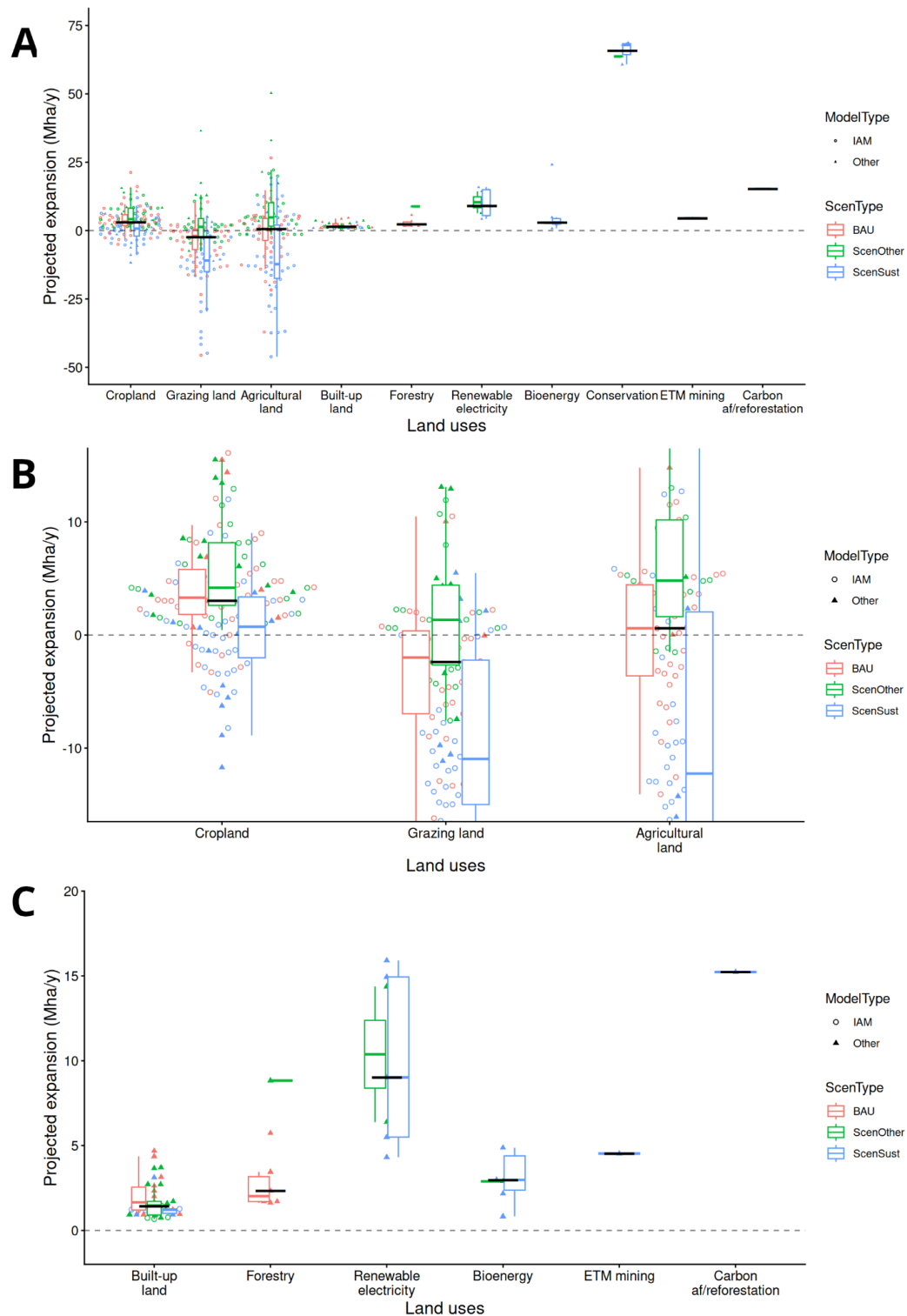


Figure 4. Global annual expansion projected in main land uses, over 2020-2050, in Mha/y. A. All land uses assessed. B. Agricultural land uses. C. Non-agricultural land uses (conservation is not displayed due to its very high value, see A.). BAU: continuation of current drivers trends, including current trends in changing demography, income, diets, productivity, etc, and the implementation of current sustainability policies. ScenSust: Scenarios described as interventions towards more sustainability (production side, consumption, policies etc). ScenOther: Other scenarios, with diverse trajectories of drivers, but with no strong emphasis on sustainability. Sources and numbers: See Supplementary Material and Supplementary Tables S3 and S4.

Land Use Change, Spillovers, and Transitions: Global Trends, Prospects, and Emerging Drivers

Submitted to Annual Review of Environment and Resources.

Supplementary Material:

This Supplementary Material is organized as follows:

- 1. Supplementary Text S1: Recent global trends of land use change**
- 2. Supplementary Text S2: Assessment of leakage and indirect land use change rates,**

including:

- Supplementary Table S1. Summary statistics on estimates of rates of leakage and indirect land use change, per broad categories of processes.
- Supplementary Table S2. Summary statistics on estimates of rates of leakage and indirect land use change, per detailed categories of processes.

- 3. Supplementary Text S3: Projections of future global land use change rates, including:**

- Supplementary Table S3. Summary statistics on projections of future land use changes, per broad categories of land uses.
- Supplementary Table S4. Summary statistics on projections of future land use changes, per categories of land uses and types of scenarios.

- 4. Literature cited in the Supplementary Material**

1. Supplementary text S1: Recent global trends of land use change

Recent global rates of land use change presented in Figure 1 were assessed as follows:

Lasting natural forest expansion (gross change):

Reference (1) reports 726,715 km² of lasting natural forest gain, corresponding to areas classed as non-tree cover in 2000 and/or 2005, which transitioned to natural tree cover by 2010, and remained as such until 2020, excluding planted trees. Of these, around 253,026 km² occurred in regions where the top two main predictors of tree cover gain is either the amount of tree cover loss or the extent of burned area, indicating that these tree cover gains are likely to result from recovery after logging or disturbance, and thus not from a genuine land use change process. We thus estimate that the actual natural forest expansion following land use change must be certainly less than 4.7 Mha/y over that period, noting that in the other regions, tree cover loss and burned areas are also important predictors.

Deforestation (gross change):

Reference (2) reports, for the representative year 2018, a total gross tree cover loss of 277,334 (+21,953) km², of which 80,435 (+10,075) Mkm² corresponds to conversion to other land uses (i.e., deforestation), including 70,027 (+9,831) km². This corresponds to a 8.04 (+- 1.01) Mha/y of deforestation, and 7.00 Mha/y in the

tropics, consistent with the 6.4 Mha/y of tropical agriculture-driven deforestation in (3).

Planted forest expansion (net change):

Reference reports a +2.82 Mha/y of planted forests expansion over 2015-2025.

Non-forest ecosystem conversion (gross change):

Reference (4) reports 173-243 Mha of non-forest ecosystem conversion over 2000-2020. This translates into 8.65 - 12.15 Mha/y over that period.

Pasture / grazing land contraction (net change):

FAO indicates a contraction of pastures globally over the recent decades, with annual rates going from +5.37 over 1984-1994 to -4.83, -6.61 and -9.15 Mha/y over 1994-2004, 2004-2014 and 2014-2024, respectively (5). We retain the latter estimate, which spans over the most recent period.

Note that the 8.65-12.15 Mha/y of non-forest ecosystem conversion and the -9.15 Mha/y of pasture contraction are entangled, as (i) the former includes some natural grazing lands being converted to other uses, and also including natural grasslands under grazing being converted to cultivated grasslands, and (ii) the latter number includes natural grasslands previously used for grazing and taken out of use.

Cropland expansion (gross):

Reference (6) indicates cropland expansion (excluding tree crops and shifting cultivation) of 101.9 Mha over 2003-2019, which we translate in an average $\sim +6.4$ Mha/y (95% confidence interval: ± 2.8 Mha/y) over 16 years.

Cropland expansion (net):

FAO reports net change in cropland accelerating from $+2.40$ and $+2.05$ Mha/y respectively over 1984-1994 and 1994-2004 to $+4.65$ and $+3.58$ Mha/y over 2004-2014 and 2014-2024 (5).

Artificialized land expansion (gross, presumed to correspond to net):

We here build a low and a high estimate. The low estimate combines the low estimate of built-up expansion of $+0.93$ Mha/y over 2015-2025 (43, 44), with low mining expansion of $+0.14$ Mha/y (48), totalling 1.07 Mha/y. The high estimate combines the $+1.97$ Mha/y from (45), with a higher mining estimate of $+0.19$ Mha/y, totalling 2.16 Mha/y.

2. Supplementary text S2: Assessment of leakage and indirect land use change rates

To assess rates of leakage and indirect land use change reported in the literature, we did not perform an original systematic search, but rather, we built on several recent systematic literature reviews and meta-analysis of land use spillovers, including: Fuller et al. (2019) (7) (systematic review of deforestation spillovers from protected areas, compiling data on spillovers from seven studies over 3404 protected areas across the globe); Ford et al. (2020) (8) (study of deforestation leakage in a pan-tropical and subtropical selection of 120 protected areas); Fuller et al. (2020) (9) (study of deforestation spillovers in 91 protected areas in Brazil); Pan et al. (2020) (10) (meta-analysis on carbon leakage in forest sectors); Ramírez-Mejía et al. (2025) (11) (systematic literature review on land use spillovers, focused on causal mechanisms); and Gliottone et al. (2026) (12) (systematic literature review on spillovers from protected areas, focused on methods).

We added some additional studies too recent to have been included in these other reviews, or discarded from these due to their respective criteria and foci but relevant for our assessment: Hertel et al. (2010) (13), Soares-Filho et al. (2010) (14), Taheripour et al. 2017 (15), Dieter et al. (2020) (16), Hu et al. (2024) (17), Seo et al. (2024) (18), Renier et al. (2025) (19), Silva and Nunes (2025) (20), Yarlagaadda et al. (2025) (21), Abman et al. 2026 (22), Barros (2026) (23).

We compiled the studies inventoried in these systematic reviews, and assessed the spillover cases reported, with a single study possibly documenting several cases of spillovers, e.g. on different study areas, or disentangling domestic and international leakage. When possible, we calculated the rate of leakage or indirect land use

change for each case reported, based on our definitions below, and a minimum and maximum rate when uncertainties were reported. Overall, we assembled a dataset of 2807 individual estimates of leakage or indirect land use change rate.

We calculated rates of **leakage** as the ratio:

(area of land use change or deforestation due to the leakage / area of land use change or deforestation avoided within the intervention scope) x 100%

Positive rates indicate leakage, while negative rates indicate “blockage”, i.e., the intervention reduced the targeted land use change (e.g., reduced deforestation) outside of the intervention scope area.

Similarly, we calculated rates of **indirect land use change** as the ratio:

(area of land use change elsewhere caused by the initial land use change / area of the initial land use change) x 100%

We used a simplified categorisation of the interventions, in order to identify major patterns. The amount of data for most interventions (except protected areas) did not allow to distinguish many subcategories or to robustly explore regional, temporal or other patterns. The categories were as follows:

Protected areas (PAs) (n=2735): public areas designated for conservation, including also, in certain studies, indigenous lands or other forms of reserves or conservation areas. This is further divided in subcategories of data coming from the three main sources, i.e. (i) Fuller et al. 2019 (n=2575), (ii) Ford et al. 2020 (n=55), (iii) Fuller et al. 2020 (n=91), as these sources have distinct methods for assessing leakage and

some have very large datasets, and (iv) all other sources (from (11, 12), and own sources) (n=14).

Forestry (n=37): including various interventions such as logging bans, moratorias or harvest reductions, REDD+ interventions, as well as reforestation policies, in certain cases supported by carbon credits schemes. This is further divided in subcategories of assessments of (i) domestic (n=15) versus (ii) international (n=22) leakage.

Supply chain (n=15): including various private-led or public interventions to influence land use change and deforestation through agricultural or forestry commodity supply chains, such as certification schemes, moratoria, zero-deforestation commitments, as well as public interventions such as due diligence regulations. This is further divided in subcategories of assessments of (i) domestic (n=6) versus (ii) international (n=9) leakage.

Agricultural policy (n=11): policies targeting agricultural lands directly such as agricultural conservation reserve programs, emissions reductions in agriculture, etc.

Indirect land use change (n=9): corresponding mostly to cases of biofuels mandates or cascading land uses in South America (sugar cane / soybean / pasture).

These categories are thematic but are often associated with certain methods and types of leakage. Leakage for PAs is usually assessed using quasi-experimental statistical approaches such as matching or difference-in-difference, in buffers of various sizes, focusing on local activity leakage. International leakage in forestry, supply chain interventions and agricultural policies is usually assessed using economic modelling, capturing market leakage, while domestic leakage in these groups corresponds to a mixed bag, including some REDD+ or reforestation projects

analyses based on matching & buffers similar to PAs, but also economic modelling similar to international leakage.

Complete data tables are available here for review:

https://www.dropbox.com/scl/fi/zbp109t8b425yhinowcnj/DataTableS2_leakage-ilucleakage_data.ods?rlkey=sbmdpl7l5o0zbd0ssm8xau56b&st=akwq64de&dl=0

and will be deposited in a public, long-term repository upon publication.

Supplementary Table S1. Summary statistics on estimates of % rates of leakage and indirect land use change, per broad categories of processes.

Broad category	mean	median	q1	q3	min	max	n
Agricultural policy	34.75	19.96	5.00	51.14	-19.05	140.00	11
Forestry	71.35	49.50	4.40	75.31	-84.00	933.33	37
Indirect land use change	205.27	80.00	20.00	101.62	1.20	808.00	9
Protected areas	20.47	-1.31	-3.63	-0.09	-3,187.25	30,707.83	2,735
Supply chain	34.85	37.50	6.70	55.25	-25.00	95.00	15

Supplementary Table S2. Summary statistics on estimates of % rates of leakage and indirect land use change, per detailed categories of processes.

Detailed categories	mean	median	q1	q3	min	max	n
Agricultural policy	34.75	19.96	5.00	51.14	-19.05	140.00	11
Forestry – domestic	91.96	4.40	0.00	55.67	-84.00	933.33	15
Forestry – international	57.29	68.25	31.53	75.31	3.84	100.00	22
Indirect land use change	205.27	80.00	20.00	101.62	1.20	808.00	9
Protected areas – Ford et al. (2020)	1,826.30	310.40	31.86	1,432.90	-3,187.25	30,707.83	55
Protected areas – Fuller et al. (2019)	-2.27	-1.28	-3.38	-0.13	-306.90	62.13	2575
Protected areas – Fuller et al. (2020)	8.33	-80.36	-89.88	-48.63	-107.41	1,645.75	91
Protected areas – other sources	-232.83	0.00	-0.96	0.00	-2,688.62	310.40	14
Supply chain – domestic	22.90	13.05	0.00	39.00	-25.00	93.02	6
Supply chain – international	42.82	40.50	10.50	61.50	2.90	95.00	9

3. Supplementary text S3: Projections of future global land use change rates

Here, we compiled data on forecasted global rates of major land use changes over the period 2020-2050. This section builds on the recent assessment by (24), which compiled business as usual (BAU) trends of major land uses, as well as the area implications of public commitments towards key land-impacting sustainability interventions, as well as several other key studies.

For each study, we reported or recalculated the projected figures of future land use changes, when reported, for the following land uses: (i) cropland, (ii) grazing land or pasture, (iii) agricultural land (usually the sum of cropland and grazing land or pasture), (iv) forestry use, and (v) urban, built up or other infrastructure land. We also reported projections of land use demand for renewable electricity and bioenergy from (24–26), conservation area from (24, 26), and ETM mining and carbon af/reforestation from (24).

For most studies, it was possible to identify area expansion over the period 2020-2050 or an overlapping period (e.g., 2010-2050, or 2020-2100). In the latter case, we calculated average yearly rates of expansion over the reported period, and applied them to the 30 years period 2020-2050, assuming that trends were thus linear over time. One study (27) reported only changes in percentage area, but without explicit indication of the baseline area. In that case, we used the base land use areas from (28) to calculate area expansion over 2020-2050.

We separated Business As Usual (BAU) from other scenarios. In most studies, BAU scenarios were identified explicitly by the authors, as the BAU, reference, or baseline scenario, including a continuation of the current dynamics without major disruption. The BAU trends compiled here correspond to projections based on continuation of current drivers trends, including current trends in changing demography, income, diets, productivity, etc, and the implementation of current sustainability policies. These are thus not necessarily continuations of current land use trends (if the trends of the underlying drivers lead to changing land use dynamics), and these also do not correspond to trends without any policy interventions. For some studies using the Shared Socio-economic Pathways as scenarios, we used the SSP2 as a reference of the closest correspondence to a BAU trend.

Other scenarios were divided in either scenarios towards sustainability, and the others. Scenarios towards sustainability were usually identified as such by the authors, as scenarios with more voluntary, ambitious or optimistic interventions, either incremental or transformative, aimed to reduce pressure on land. For studies using the Shared Socio-economic Pathways as scenarios, we used the SSP1 as a scenario with ambitious sustainability interventions. Non-sustainability scenarios

were usually assumptions about higher land demand due to higher consumption, pessimistic trends about land productivity, or other disruptions.

The inventoried studies are: FAO (2012) (29), Fischer et al. (2012) (30), Bajželj et al. (2014) (31), Tilman and Clark (2014) (32), Hertel et al. (2016) (33), FAO (2018) (34), Rogelj et al. (2018) (35), Tallis et al. (2018) (36), Huang et al. (2019) (37), Nepal et al. (2019) (38), Saerchinger et al. (2019) (39), Stehfest et al. (2019) (40), Willett et al. (2019) (41), Zhou et al. (2019) (42), Chen et al. (2020) (43), Mora et al. (2020) (44), Rabin et al. (2020) (45), Mishra et al. (2021) (46), Bodirsky et al. (2022) (47), FAO (2022) (48), Simkin et al. (2022) (49), Searchinger et al. (2023) (50), Gurgel et al. (2024) (25), Humpenöder et al. (2024) (51), Weindl et al. (2024) (52), Maestre et al. (2025) (53), Molina Bacca et al. (2025) (54), Renier et al. (2025) (24), Rockstrom et al. (2025) (55), Brock et al. (2026) (26), Gibson et al. (2026) (27), Güneralp and Ahasan (2026) (56), Polasky et al. (2026) (57).

Complete data tables are available here for review:

https://www.dropbox.com/scl/fi/10eplt9oq17hgyczpujimp/DataTableS5_prospective.xlsx?rlkey=8iq2q5pdrol4b4vygp4nmcfjh&st=4wxxbyxe&dl=0

and will be deposited in a public, long-term repository upon publication.

Supplementary Table S3. Summary statistics on projections of future land use changes, per broad categories of land uses, in Mha/y over 2020-2050.

[illegible]

Supplementary Table S4. Summary statistics on projections of future land use changes, per categories of land uses and types of scenarios, in Mha/y over 2020-2050.

Land use	ScenType	mean	median	q1	q3	min	max	n
Cropland	BAU	4.32	3.31	1.83	5.81	-5.05	21.25	54
Cropland	ScenOther	5.72	4.18	2.62	8.17	0.44	15.50	39
Cropland	ScenSust	0.45	0.73	-2.02	3.37	-11.71	12.00	55
Grazing land	BAU	-4.27	-1.99	-6.96	0.36	-45.59	10.49	45
Grazing land	ScenOther	2.77	1.34	-2.64	4.41	-7.57	36.45	35
Grazing land	ScenSust	-12.54	-10.96	-14.99	-2.22	-44.83	5.48	40
Agricultural land	BAU	-0.82	0.59	-3.61	4.44	-37.11	26.59	46
Agricultural land	ScenOther	8.33	4.81	1.62	10.17	-1.52	50.33	35
Agricultural land	ScenSust	-12.04	-12.25	-17.49	2.04	-103.11	19.27	47
Built-up land	BAU	2.08	1.66	1.20	2.55	0.93	4.68	14
Built-up land	ScenOther	1.65	1.47	0.91	1.71	0.67	3.71	17
Built-up land	ScenSust	1.45	1.22	1.01	1.26	0.93	3.12	6
Forestry	BAU	2.76	2.02	1.70	3.17	1.63	5.73	6
Forestry	ScenOther	8.83	8.83	8.83	8.83	8.83	8.83	1
Renewable electricity	ScenOther	10.38	10.38	8.38	12.38	6.38	14.38	2
Renewable electricity	ScenSust	9.94	9.02	5.50	14.94	4.31	15.91	5
Bioenergy	ScenOther	2.89	2.89	2.89	2.89	2.89	2.89	1

Bioenergy	ScenSust	6.33	2.98	2.37	4.40	0.83	24.17	6
Conservation	ScenOther	63.71	63.71	63.71	63.71	63.71	63.71	1
Conservation	ScenSust	65.82	67.90	64.34	68.35	60.77	68.79	3
ETM mining	ScenSust	4.53	4.53	4.53	4.53	4.53	4.53	1
Carbon af/reforestation	ScenSust	15.23	15.23	15.23	15.23	15.23	15.23	1

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