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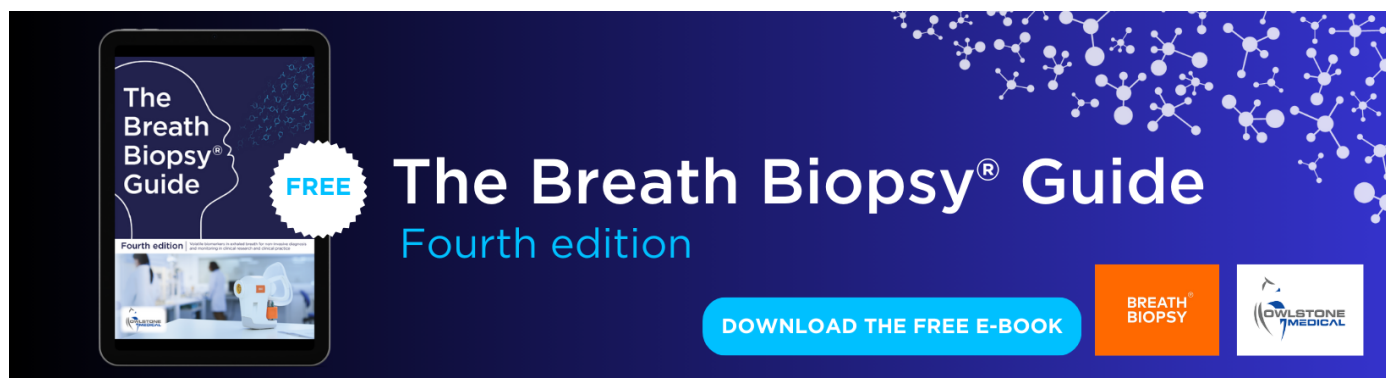
## Tipping point dynamics in global land use

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## LETTER

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E-mail: [cat2180@columbia.edu](mailto:cat2180@columbia.edu)**Keywords:** global land use, development, agriculture, historical geography, social tipping pointsSupplementary material for this article is available [online](#)**Abstract**

Agricultural land use has recently peaked, both globally and across country income groups, after centuries of expansion and intensification. Such shifts in the evolution of global land use have implications for food security, biodiversity loss, and carbon emissions. While economic growth and land use are closely linked, it is difficult to determine the extent to which the relationship is causal, deterministic, and unidirectional. Here we utilize gridded datasets to study long-term global land use change from 1780 to 2010. We find evidence for an economic tipping point, where land use intensifies with economic development at low income levels, then reverses after incomes reach a critical threshold. Cropland peaks around \$5000 GDP per capita then declines. We utilize a Markov model to show that this reversal emerges from a variety of divergent land use pathways, in particular the expansion of protected areas and a reduction in land use lock-in. Our results suggest that economic development remains a powerful driver of land use change with implications for the future of natural ecosystems in the context of continued population and income growth.

**1. Introduction**

Land use patterns have changed dramatically since the Industrial Revolution in response to changes in resource usage, food production and agricultural intensification, population growth and urbanization, and global interdependence and trade. These rapid changes have shaped the natural environment at a local and global level, fundamentally altering nutrient cycles, terrestrial cover, and biodiversity (Turner and Meyer 1994, Vitousek *et al* 1997, Tilman *et al* 2001, Sanderson *et al* 2002, UNEP 2002, Foley *et al* 2005).

Global human-appropriated land area has plateaued since 1950 after more than a century of exponential growth (SI 1 (available online at [stacks.iop.org/ERL/16/125012/mmedia](https://stacks.iop.org/ERL/16/125012/mmedia))). This rapid shift in the dynamics of land use change represents a potential regime shift in global land use, and understanding its causes and future evolution is necessary for addressing biodiversity loss, food security, and climate change. For the latter, land use dynamics inform assessments of past and future

climate change (Feddema *et al* 2005, Betts *et al* 2007, Stehfest *et al* 2019, Hurtt *et al* 2020) given that land use change is a major driver of emissions, contributing almost half of the cumulative emissions from fossil fuels (Houghton 1999, Friedlingstein *et al* 2019, Gasser *et al* 2020).

Tipping points are critical thresholds beyond which a system's behavior changes with long-term consequences (Scheffer *et al* 2009), and are an important feature of the climate system (Lenton *et al* 2019), ecological systems (Folke *et al* 2004, Andersen *et al* 2009, Runyan and D'Odorico 2016), and social systems (Kopp *et al* 2016, Van Ginkel *et al* 2020). Within the context of coupled social-environmental systems, tipping points generally have multiple causes and cascading effects, undermining a capacity to predict future system behavior (Milkoreit *et al* 2018). In this paper, we investigate recent land use change as the potential consequence of a tipping point within local and global social-environmental systems, and the role of a single driver, income levels, to explain and predict these changes.

Historical land use patterns are a product of the landscape's natural characteristics like climate, vegetation, and soil suitability, as well as human factors including population levels, economic development, technological availability, and policy. Agriculture is the primary driver of land use change, with one-third of the world's habitable land used for either cropland or pasture (Ramankutty *et al* 2008). Pressure on terrestrial resources for food and biomass will increase as economic development raises more people out of poverty, especially if global demand increases for land-intensive livestock products (Sage 1994, Popp *et al* 2017). Globally, 70 Mkm<sup>2</sup> of non-desert and non-tundra land remains unappropriated to human use, compared to the current global cropland extent of 14–18 Mkm<sup>2</sup> (Ramankutty and Foley 1999, Klein Goldewijk *et al* 2011) and pastureland of 28 Mkm<sup>2</sup> (Klein Goldewijk *et al* 2011). In light of this remaining land potential, the recent plateau in land use appropriation is all the more surprising. While broad patterns of anthropogenic land use change have been generalized (Ellis *et al* 2010, Mustard *et al* 2012), they vary across time, biomes, and spatial scale, and the economic mechanisms are often poorly understood (Irwin and Geoghegan 2001, Lambin *et al* 2001).

In this paper we analyze the long-term trends in land use and their relationship to economic development over the course of centuries. In particular, we aim to provide empirical evidence to address a theory of sequential land use change developed and referenced in several papers including DeFries *et al* (2004), Foley *et al* (2005) and Mustard *et al* (2012). In this conceptual model, hereafter the 'MDF model', economic development coincides with a sequence of land-use transitions: natural ecosystems become frontier clearings and then small-scale or subsistence agriculture and then intensive agriculture. At latter stages of development there is a concurrent increase in urban and protected land. Such patterns have been observed in the continental US and Europe where agricultural land has reverted to forests (Williams 1992, MacCleery 1993, Barrett 1994, UNECE 1996) driven by productivity improvements. More recent examples of forest recovery include Puerto Rico (Grau *et al* 2003), Ecuador (Rudel *et al* 2002), and China (Ramankutty and Foley 1999), among others.

Our core finding is that land use responds to economic development in a broadly consistent manner across regions and time frames. We show that a regime shift has occurred in aggregate and local land use change, and that an economic tipping point exists which drives this regime shift. Our results help inform multiple land use debates, including the Borlaug hypothesis, forest transition theory, and the potential displacement of resource production from rich to poor countries.

## 2. Materials and methods

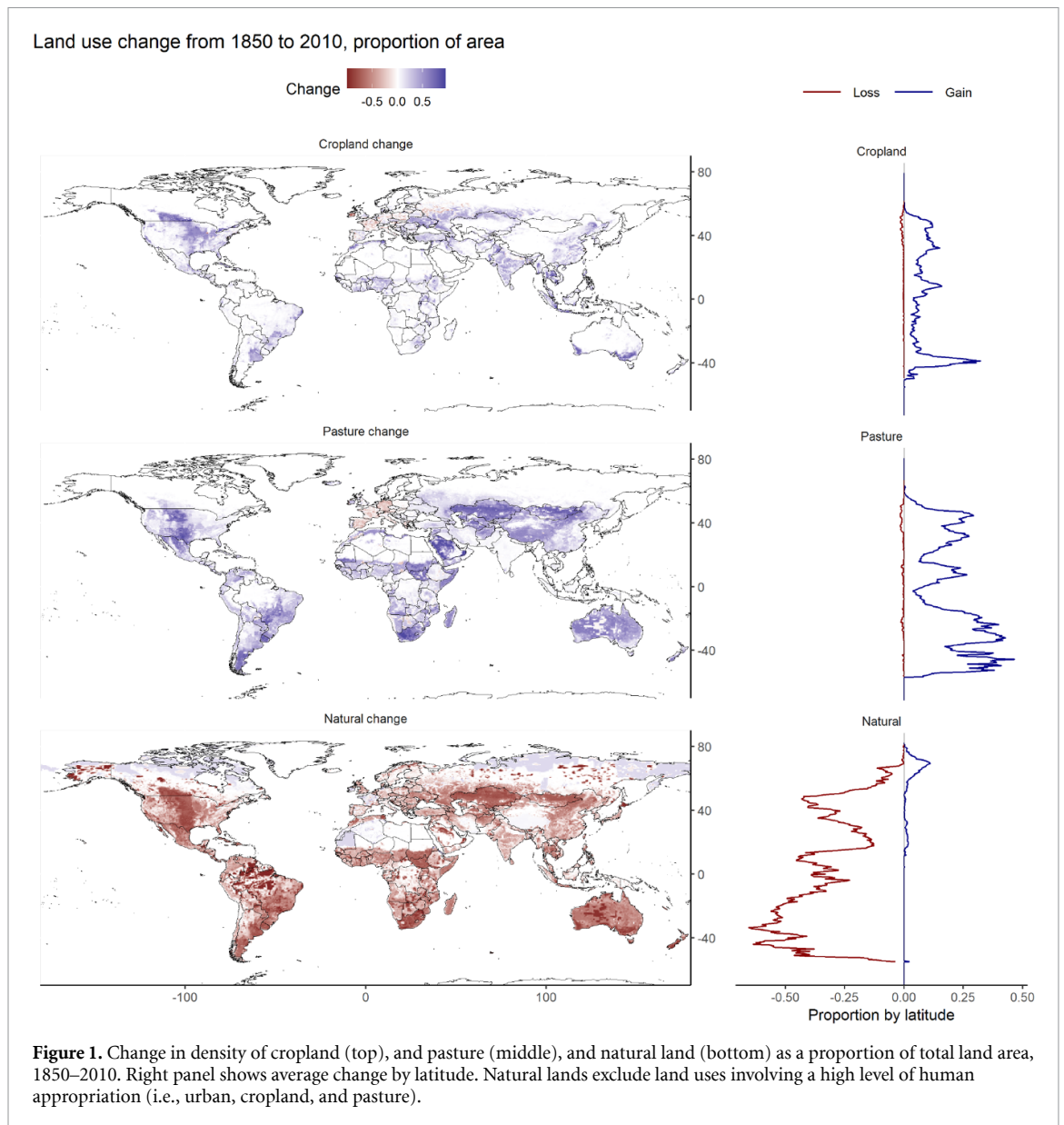
We construct a land use dataset consistent with the categories in the MDF model by combining gridded historical land use data (Klein Goldewijk *et al* 2011, Meiyappan and Jain 2012) with protected area (UNEP-WCMC, IUCN 2018) and socioeconomic data (Klein Goldewijk *et al* 2017, Inklaar *et al* 2018) (see SI 2). The resulting product is a decadal dataset from 1780 to 2010 at 0.5° resolution (a grid cell spacing of approximately 55 km at the equator).

We use this dataset to test whether observed land transitions follow the pattern presented in the MDF Model, and to what extent such changes are driven by economic development. This empirical analysis presents a fundamental challenge: while rising incomes are expected to influence land use, land use change is a key driver of economic development—presenting a feedback loop or endogenous relationship.

A further challenge stems from the multi-scale nature of land use change, with local interactions between people and the land they live on, as well as migration and economic drivers at the regional and global scales. The ongoing global redistribution of agricultural activity could, in principle, shift lands into and out of agriculture while leaving net agricultural area unchanged globally. While the MDF model isolates local-scale dynamics, this study engages with scale explicitly, identifying land use dynamics at the grid cell, national, and global levels and their interconnections. We investigate the limitations of the spatial resolution of our data in SI 3.

To address these methodological challenges, we utilize two approaches to study tipping point dynamics and scale issues. First, we present a regression-based approach, where we control for the feedback drivers across time and space. This allows us to test for the presence of a land use tipping point, in which cropland area increases with income growth up until a point of development after which it declines. Model specification details are in SI 7.

Second, we treat the combined land use-economic system as a unit and study the characteristic transitions using a Hidden Markov model approach (Usher 1981, Depauw *et al* 2019, McClintock *et al* 2020). Markov chain models allow us to study the properties that result in a tipping point as an emergent phenomenon including path dependence at the pixel level (Geoghegan *et al* 1998) and the potential for lock-in, non-determinism, and non-unidirectional change. This analysis produces an empirical analog to the state-based MDF model. The premise behind such phased models of land use is that the human appropriation of land follows a common pattern across otherwise dissimilar regions. To translate that intuition into an empirical model, we estimate a set of characteristic land use states consistent



with observed grid cell-level transitions. The outcome of this process is a Markov model, where states reflect the common land uses characterized both by the share of each land use class and by the probability that they transition to other hidden states. A simplified diagram of the method is shown in figure SI 5.1 and details are in SI 5.

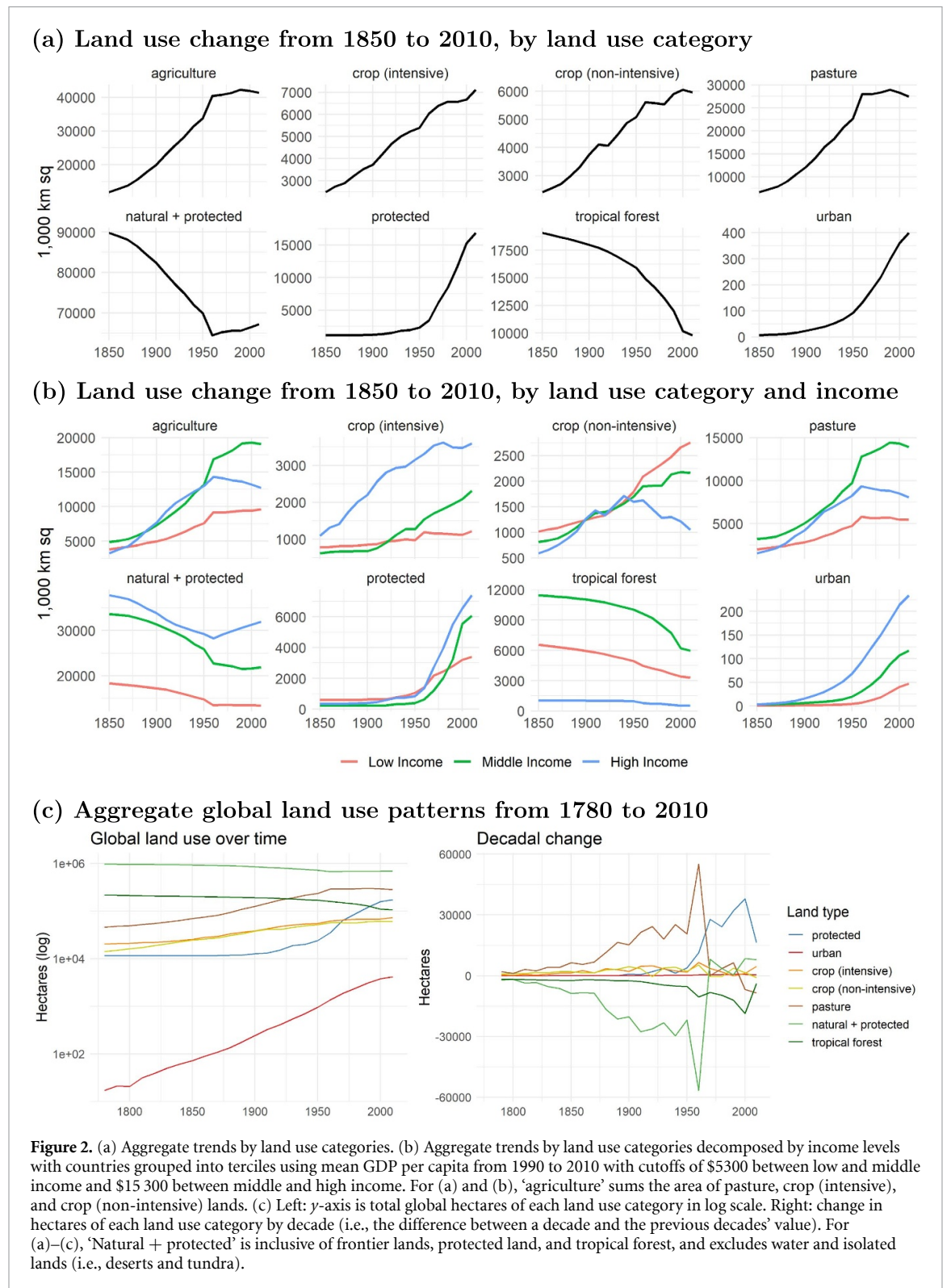
### 3. Results

#### 3.1. Historical trends

The defining feature of global land use since 1850 has been the loss of natural lands and the increase in agricultural lands, as visualized in figure 1. While pastureland increased more than cropland, both have increased across all habitable regions: croplands grew to encompass an average of 5% of the land spanning each  $0.5^\circ$  latitude band with a human presence, while pastureland grew to encompass 13%, on average. But significant variation in this pattern exists

at the temporal and regional level. For most of the last 170 years, the area of natural lands (defined as non-agricultural and non-urban land), decreased at an accelerating pace. Figure 2(a) shows that this pattern changed around 1960 when aggregate land conversion halted and natural lands began to recover. The global extent of agricultural land, including pasture and cropland, shows the inverse pattern, increasing until 1960 before plateauing. Several studies have noted this global plateauing in cropland area (Ausubel *et al* 2013, Ramankutty *et al* 2018) and decline in agricultural land across regions like North America, Eurasia, and China (Ramankutty and Foley 1999).

It is worth noting that while abandoned agricultural lands generally revert to historical vegetative cover, primarily forest or grassland, this does not imply a recovery in the ecological health and biodiversity of the prior undisturbed state (Rudel *et al* 2005, Queiroz *et al* 2014,

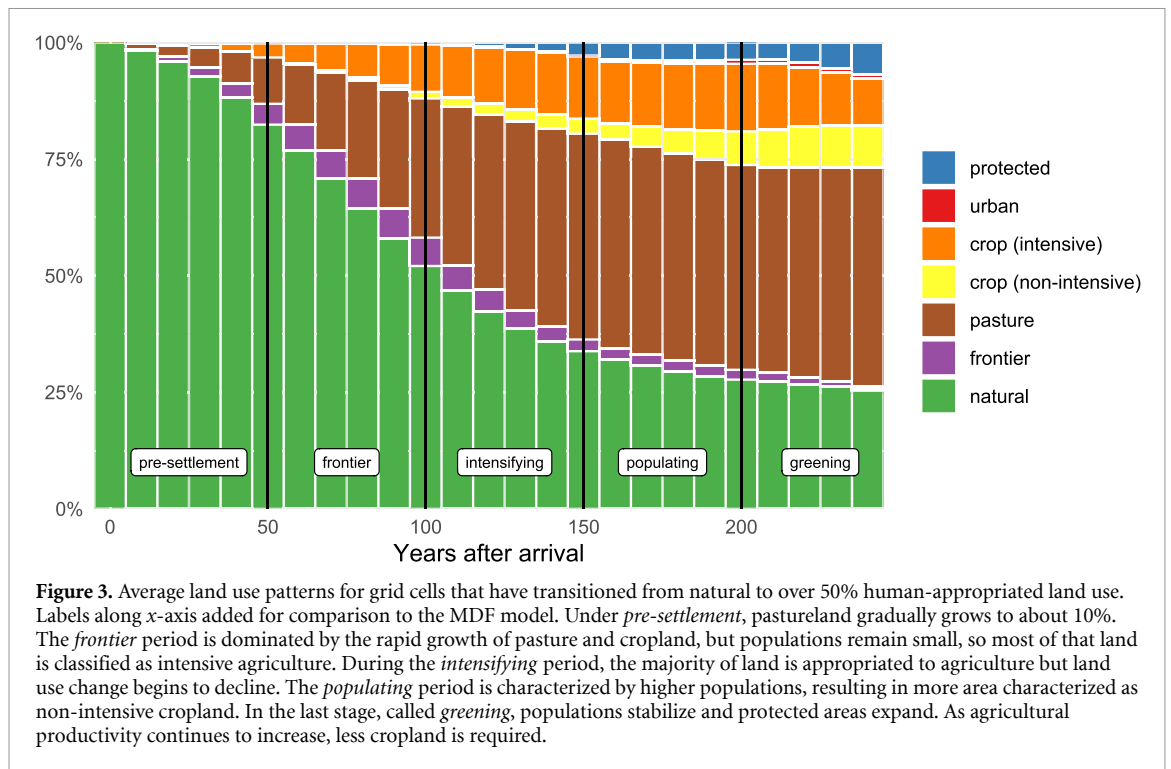


Runyan and D'Odorico 2016). Likewise, this reduction in agricultural land has coincided with agricultural intensification, and while intensification does not directly contribute to land use change, it has environmental impacts through habitat loss (Tscharntke *et al* 2012), nutrient run-off (Bodirsky and Müller 2014), greenhouse gas emissions (Smith *et al* 2013), fire activity change (Andela *et al* 2017), and surface water area (Pekel *et al* 2016).

Furthermore, the increase in protected areas contributes to this observed trend, but we do not attempt to measure the quality of protection. Some protected areas may simply be 'paper parks' with few actual protective mechanisms or government enforcement (Bruner *et al* 2001).

Urbanization has grown quickly in relative terms but remains a very small portion of human land appropriation. However, urbanization has an impact





on land use beyond its immediate footprint via effects on demand for food, water, biomass, energy, and waste services, environmental amenities, and adjacent land prices (Vitousek *et al* 1997).

As shown in figure 2(b), we see a stabilization in agricultural land use and in natural and protected lands across income levels. Richer countries reached their peak level of agricultural expansion in 1960 and declined thereafter. While poorer countries are still modestly increasing their agricultural land area, the rate of land conversion dropped significantly starting in 1960. Middle income countries did not peak until 2000, and they are still in the process of converting their low intensity croplands to intensive use<sup>3</sup>, while low income countries are still expanding non-intensive cropland. While tropical forest loss has declined to historical lows, it has yet to fully plateau in low income countries (mainly in Central Africa and Indonesia).

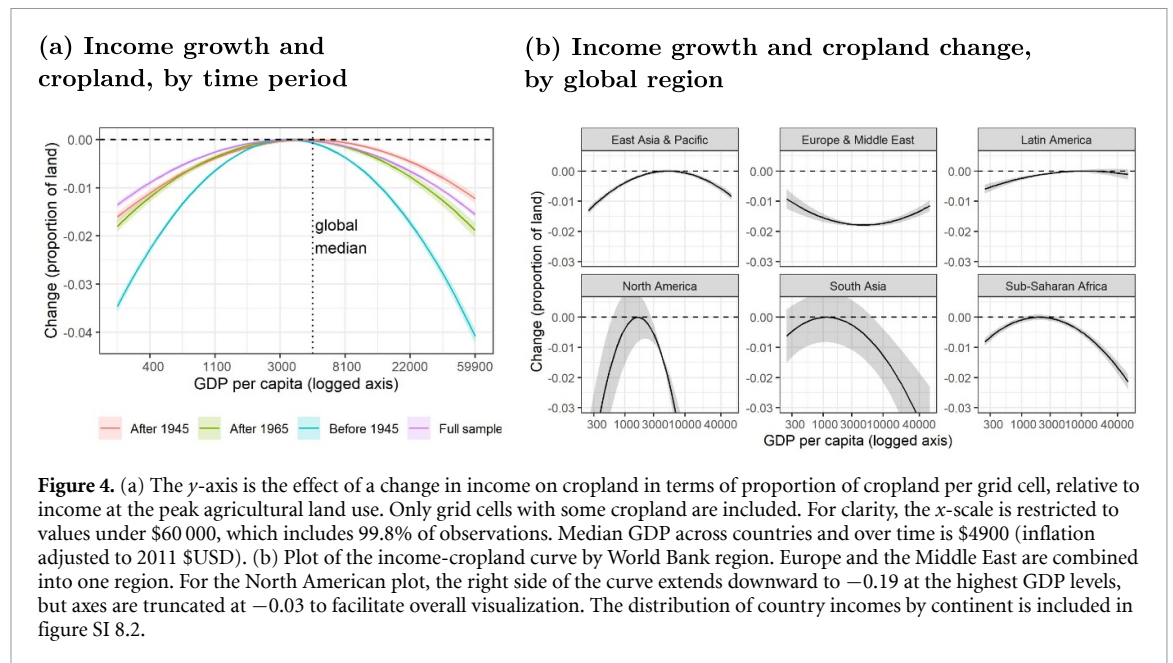
In line with forest transition theory (Mather and Needle 1998, Rudel *et al* 2005), wealthy regions of Europe and North America underwent significant reforestation after a period of agricultural intensification in the late 19th and early 20th century (MacCleery 1993). As detailed later, our empirical methods support the hypothesis that this pattern is driven by economic growth, and that continued economic growth will further increase the extent of natural land. Taken together, we argue this represents a regime shift in the drivers of global land use change,

characterized by increasing food production through changes in land management rather than increasing lands under cultivation.

At the local level, a similar shift has occurred. Figure 3 charts the average evolution of land use for a grid cell that went from being completely natural to a majority of human-appropriated land use within our historical record. While there is general alignment with the MDF Model, some distinct differences emerge (see SI 6). First, natural lands remain a large proportion of grid cells (>25% on average), even as human land use patterns mature. Second, intensive agriculture is a common land use early in the appropriation process, and is not necessary preceded by subsistence or non-intensive agriculture—although this could reflect the recent time span under consideration. Once agriculture amounts to 50% of a grid cell's land use, further 'intensification' is characterized by the growth of human population centers. Third, we identify a final period of land use change in the most recent decades, *greening*, characterized by stabilizing and declining agricultural land use and increasing protected lands.

The last two centuries have also seen a massive increase in wealth, with incomes rising almost everywhere in the world. Average real PPP-adjusted GDP per capita are estimated to have increased ten-fold between 1820 and 2010 (Bolt *et al* 2014). As an alternative approach to assessing the MDF model, we can study the evolution of land use as a function of income, rather than time (see figure SI 4.1). We again see a pattern where natural land is increasingly converted to cropland up until a point of wealth when agriculture use plateaus and protected lands

<sup>3</sup> Our measure of low intensity croplands is distinct from subsistence agriculture (see section SI 2.1).



increase. Countries that were colonized, including Australia, South Africa, and those in the Americas, see the greatest reductions in natural land coverage during our study period.

We replicate this analysis using biomes and climate zones rather than countries in SI 8. Taken together, a story emerges suggesting that a tipping point in global land use has been reached in which agricultural land use is declining and natural and protected lands are increasing.

### 3.2. Land use tipping point

The regression models specified in SI 7 show that income is significantly associated with land use change. Figure 4(a) plots the average effect of income (GDP per capita) on land use change. Since our income data is at the national level, this result describes the expected change in land use within a country given a change in its average income. As countries get wealthier from a poor baseline, natural lands are converted to agriculture at a rate that slows and then reverses. Cropland area peaks at \$5000 GDP per capita and then declines as incomes rise. Likewise, loss of natural land area peaks around this same income level (see figure SI 7.1).

The underlying dynamics of this tipping point appear to be similar across time periods and regions. Technology has shaped global land use: the moldboard plow in the late 19th century facilitated the mass conversion of deep-rooted grassland to cropland, and breakthroughs in crop genetics during Green Revolution in the 1960s increased the productivity of marginal lands. However, the inverted-U relationship has remained consistent over our dataset. Figure 4(a) splits the sample into time periods, one through 1945, one after 1945, and one after 1965. We see similar concave curves for cropland change in

each era, with the pre-war curve the steepest. We next test this relationship across global regions and find that the inverted-U curve holds in each case except for Europe and the Middle East.

While our results suggest that income is a major driver of land use, it is worth noting that policy also plays a major role. Policy factors could help explain the different pattern we observe in Europe and the Middle East—especially if governments are encouraging certain land uses for political, aesthetic, or strategic reasons. European agriculture, for example, is highly subsidized through the EU's Common Agricultural Policy, where the average hectare of agricultural land receives \$358 per year, an amount that is 48% greater than in the US (CRS 2021). European countries have had higher agricultural subsidies than the rest of the world since 1960, on average (see figure SI 8.6). And as major food importers, some Middle Eastern countries have prioritized food security and enacted policies involving large subsidies to farmers and public investments in irrigation (Lippman 2010).

Other examples of large-scale policies that altered land use trends include the Homestead Act in the US, which encouraged the conversion of millions of acres from prairie and forest to agriculture in the late 19th century, the USSR's frontier lands program in the 1950s, and liming and fertilization initiatives of the Cerrado of Brazil in the 1980s to make it suitable for agriculture (Correa and Schmidt 2014). On the other hand, China has undertaken a massive reforestation program in recent decades affecting over ten million hectares of former cropland (Delang and Yuan 2016). We include an empirical test of the role of agricultural subsidy policy on cropland area in the Possible Drivers section.

Given that GDP per capita represents a national average and says little about the distribution of



**Figure 5.** (a), (b) States identified by the hidden Markov model (bars), and their major transitions (arrows). The x-axis is the percent of a pixel's land use. The labels for each hidden state (along left) are provided for interpretation. Transition probabilities are per decade. (a) The Markov model is estimated using land use information alone, including transition probabilities greater than 2.5%. (b) The Markov model is estimated using land use information and income quantiles. Boxes denote states in each tercile of the income distribution, with labels 'poor', 'medium', and 'rich' denoting these terciles, including transition probabilities greater than 2.5%. (c) The probability for each state (labeled on left) of transitioning to a state with more natural and protected land (right of 0% label) or less (left of 0%).

income, we also test the tipping point by country-level income inequality in SI 8, where we find the curve becomes more pronounced at greater levels of inequality.

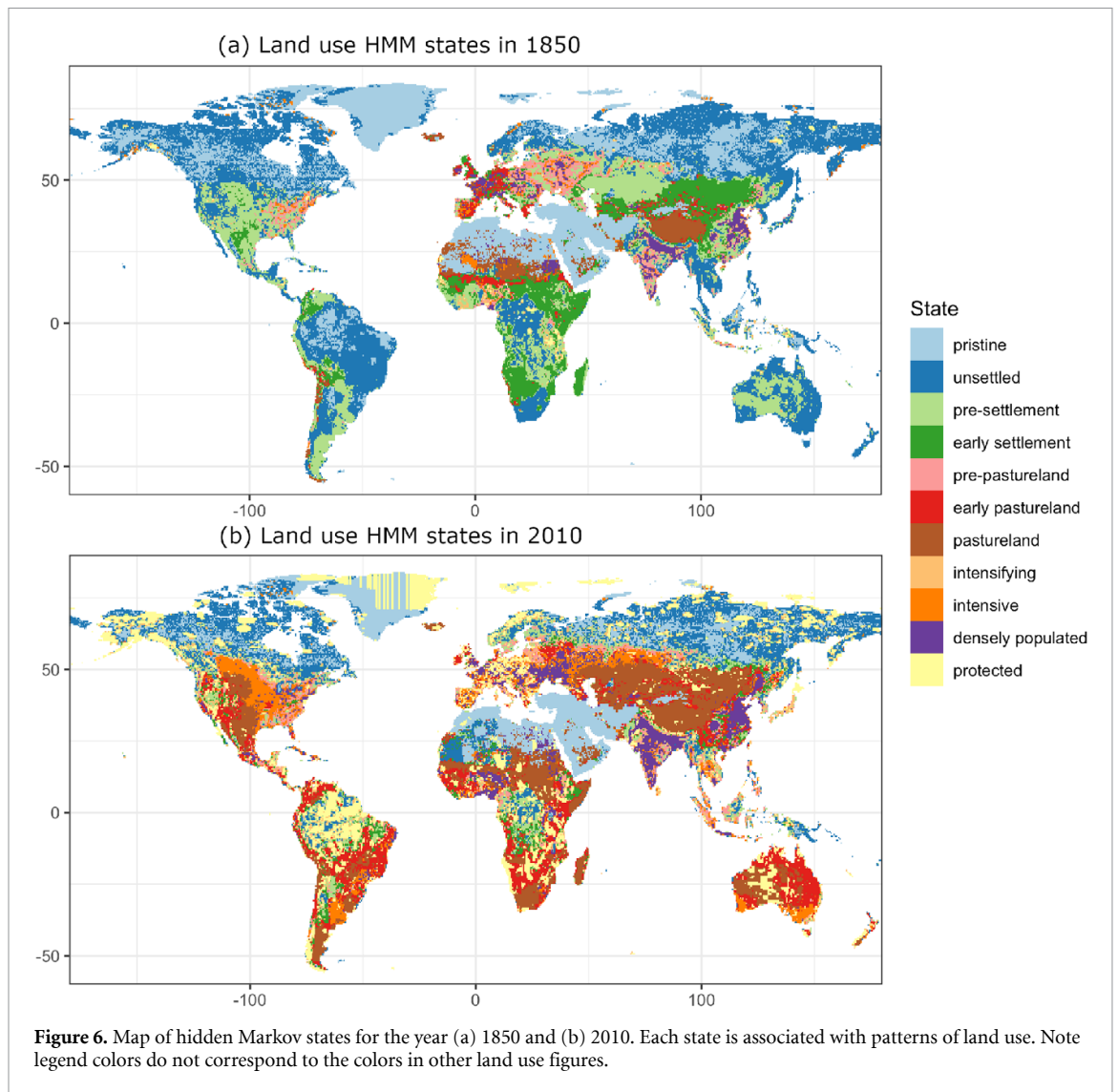
### 3.3. Markov modeling

We next estimate a Hidden Markov model that represents the characteristic land use transitions observed at the local (grid cell) level. This complements the regression analysis by disaggregating land use regime transitions that lead to the tipping point. The analysis is performed in two ways: first using land use types only, which assumes that any effect of income on land use dynamics is reflected in the observed land use pattern, as in the MDF model. Second, we explicitly include an income metric to define the hidden states.

Without including income, we identify 11 states as shown in figure 5(a) which show strong sequential

steps consistent with the MDF model from *pristine* lands (100% natural) to the *early settlement* state. From the *early settlement* state, we observe a bifurcation in which the most likely states that follow are *pre-pastureland* (13% of cells per decade) and *intensifying* (4%). If a cell enters the *pre-pastureland* state, then pastureland rapidly expands to appropriate the majority of available land. Pastureland shows considerable lock-in: of the 10% of pixels that enter a *pastureland* state or one of its immediate precursors, 79% never exit. Pastureland lock-in is at least partly an emergent process, and does not appear to be predetermined by climatological conditions (see figure SI 9.5). Unlike lock-in dynamics of urban land use studied elsewhere (e.g. Barter 2004, Reyna and Chester 2015), pastureland lock-in is likely driven by environmental and institutional changes (Milchunas and Lauenroth 1993, Specht 2019). Land that enters the *intensifying* state generally proceeds to





the *densely populated* state. We also identify a distinct state with a majority of protected land use.

We map the spatial patterns of the hidden states in figure 6 in 1850 and 2010. Much of the world in 1850 is classified as *unsettled*, *pre-settlement*, and *early settlement* due to the high portion of natural land. By 2010, much of this area is converted to *pastureland*, with *pristine* and *unsettled* states concentrated in extreme environments, near the poles and the Sahara. Bordering unsettled areas are *pre-settlement* and *early settlement* lands. Elsewhere, a concentric layered pattern appears, with *densely populated* regions couched within *intensive* areas, which border expanses of *pastureland*.

When income is explicitly included as a state attribute, 16 hidden states are identified (see figure 5(b)). Here, most transitions occur across income groups and between corresponding land use states at different income levels. For example, *pre-settlement poor* land commonly transitions to the *pre-settlement middle* state and then the *pre-settlement rich* state due to rising incomes in the

surrounding country. However, this path dependence is less deterministic than in the pastureland lock-in described previously: amongst pixels that occupy a given land use type after the income has grown to middle or rich levels, 64% are observed to leave their land use type. Moreover, the areas that do transition to other land uses are concentrated in rich countries (e.g. US, Canada, Europe, Australia), suggesting that this dynamic reflects the rapid growth in income as opposed to land use lock-in.

To relate these results to the regression analysis above, we consider the probability that unappropriated land (natural and protected land) increases or decreases following each state. While only one state in each of the poor and middle income groups shows a greater probability of increase in unappropriated land, half of the high income group states do. Natural land is found to decrease in low and middle income groups, but increase at high incomes.

The Hidden Markov model can also be used to simulate land use changes by iteratively applying the

transition matrix to a state vector (see figure SI 9.4). While the reduction in natural land occurs more rapidly in the model accounting for income, this model eventually projects a reversal of natural land appropriation. The model without income shows no such reverse.

Overall the Markov analysis suggests that land use is greatly influenced by land use in earlier periods and by income growth. We find that land use dynamics are different in Europe and Asia than in the Americas and Australia, and that these differences persist. Key bifurcations early-on can shape prospects for future land intensification and urbanization, suggesting that land uses generally shift more slowly than incomes rise. At higher incomes, however, most state transitions are characterized by increases in natural land, and the potential for lock-in is less.

### 3.4. Possible drivers

We now examine possible mechanisms for the tipping point relationships found above. We know that as incomes and population levels have increased across our study period, demand for agricultural products has increased. The recent decline in agricultural land area corresponds to a shift from extensification (i.e. increasing production through expanding cropland) to intensification i.e. (increasing production through inputs and management changes). Multiple explanations are plausible for this extensive-intensive shift in relation to changes in income, population, agricultural productivity, and trade, some of which can support a reversal in the loss of natural land. Using data from the last 60 years, we now provide evidence to inform our theoretical explanations which is further expanded upon in the Discussion section below.

Economic theory provides insights into the drivers of land use change (Lewis 1954, Ranis and Fei 1961, Harris and Todaro 1970). As societies get wealthier, higher consumption levels require more land devoted to food production. With economic growth, more capital is available for agricultural intensification. Increased productivity spurs population growth, further pressuring natural resources. Arable land eventually becomes scarce and the relative return on intensifying existing cropland increases. Once a certain level of income is reached, birthrates decline and people increasingly concentrate in urban areas as non-farm wages rise with economic productivity. Despite increasing consumption, a declining (or stable) rural population combined with a highly productive agricultural sector begins to ease land pressures. Marginal cropland reverts to its natural state. At the same time, wealthier places may value environmental amenities and land conservation more highly, driving increased investments in protected area (Jacobsen and Hanley 2009, Frank and Schlenker 2016). Together these dynamics suggest a economic tipping point in which cropland

plateaus and declines while natural and protected lands recover.

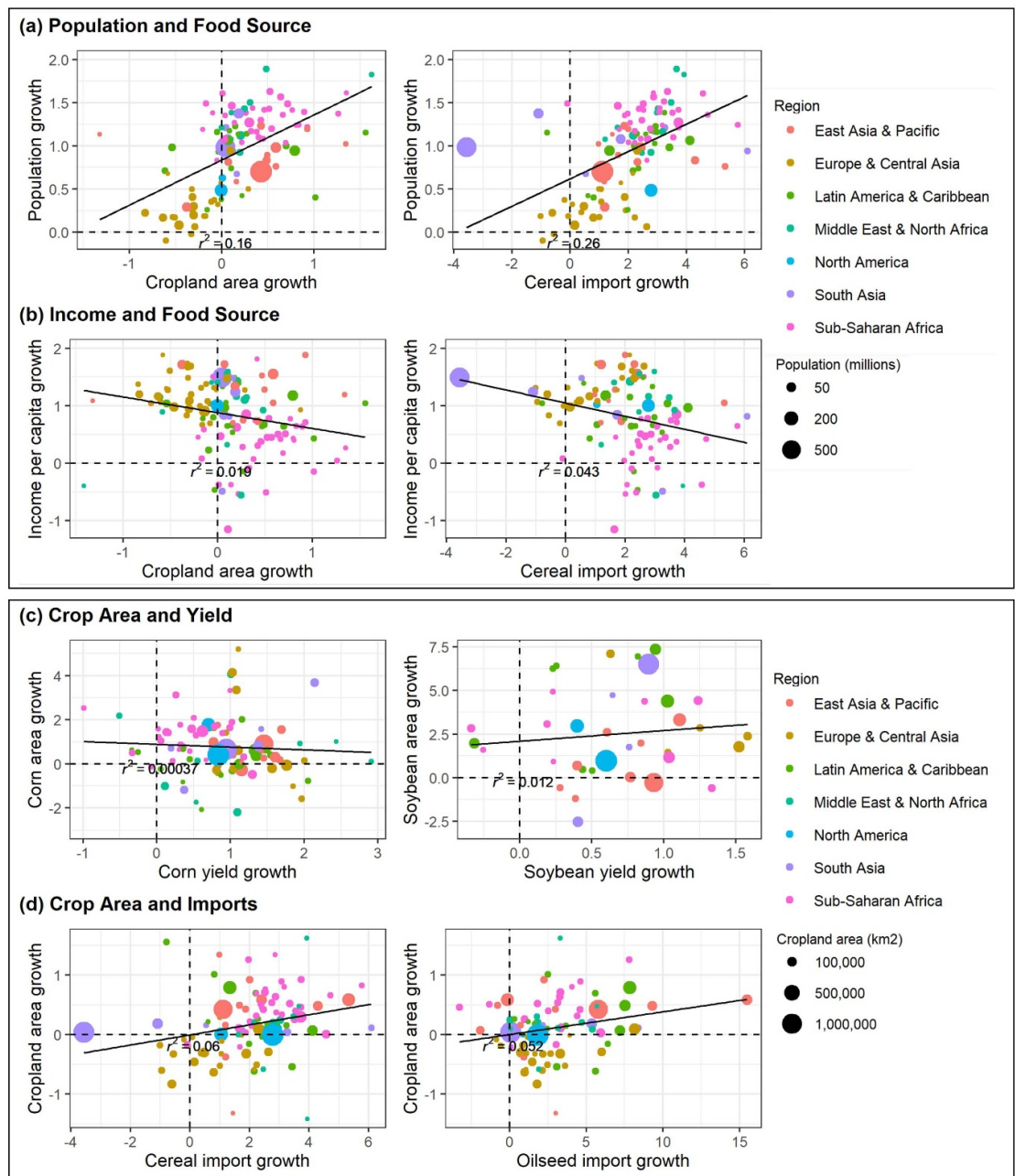
Our tipping point is related to the ‘Kuznets curve’ concept, developed to explain why inequality tended to increase and then decrease with economic development (Kuznets 1955). This model has been applied to explain the increase and subsequent decrease in environmental degradation with income levels. Grossman and Krueger (1995) find that pollution begins to decline at a per capita income of \$8000, and in the context of land use, Cropper and Griffiths (1994) find that deforestation declines in Latin America and Africa once incomes surpass \$5000 per capita. While this forest-income relationship has been questioned (Koop and Tole 1999), we note an overall similarity of these values and our land use tipping point estimate of \$5000.

However, several important features distinguish our analysis from the environmental Kuznets curve (EKC) literature. First, while traditional EKC work describes a trade-off between economic production and an immediate social ill (i.e., pollution), changes in land use provide less immediate benefits and may entail different motivations. Second, EKC analyses often look at ‘flows’ in terms of pollution rates while we focus on ‘stocks’ of land. Our paper shows a reversal process in which land is removed from human use, not just reductions in rates. Finally, land use patterns have long-term consequences for economic growth, just as economic growth has consequences for land use change. This feedback loop motivates our Markov analysis. Unlike most EKC interpretations, we propose that the full description of the system includes how land use and income change together.

Population and income growth are strong drivers of land use change, but act in opposite directions. We find that population growth, which was at its highest rate in the second half of the 20th century, is positively associated with recent cropland expansion and food import growth (i.e., more mouths to feed), while income growth is negatively associated with changes in cropland area and food imports, implying a process of intensification. Results are shown in panels (a) and (b) of figure 7.

To assess the role of agricultural productivity, we compare country-level growth in yield and harvested area of several staple crops using FAO data over fifty years from 1960 to 2010. Yields have increased greatly in nearly every country, with a mean increase of 84% for corn and 64% for soybeans. While most countries increased soybean area, corn area remained constant or declined in many cases. Overall we see little correlation between yield and area under production, as shown in panel (c) of figure 7 for corn and soybeans and figure SI 8.4 for wheat, suggesting that yield trends alone do not drive expansions or contractions in agricultural area.

## Drivers of land use change, 1960-2010



**Figure 7.** Country-level growth relationships from 1960 to 2010. Panel (a) plots growth in population (y-axis) and growth in cropland area and cereal imports (x-axis), whereas (b) plots growth in income per capita on the y-axis. Panel (c) plots growth in crop area (y-axis) and yield (x-axis) for corn (left) and soybeans (right), whereas (d) plots import growth for cereals (left) and oilseeds (right) on the x-axis. Colors denote World Bank regions. Size of point corresponds to country population for panels (a), (b) and cropland area for panels (c), (d). Growth rates are the log difference of the values for 2010 and 1960. For either end point, a five-year forward window is averaged (i.e. 1960 is the average of 1960–1965) to reduce the effect of country-year anomalies and data gaps. Countries with no cropland are excluded and scales are trimmed to omit countries with negligible cropland area. Data on crop production and import growth from FAOSTAT.

Reductions in cropland in rich countries could also reflect a shift in production to poorer countries, with a corresponding increase in imports. We evaluate the relationship between growth in cropland area and imports of both cereal crops and oil seeds, the main sources of human and livestock caloric intake. Again, we see no strong relationship, as shown in panel (d) of figure 7. If anything, there

is a positive correlation in which countries simultaneously increase cropland area and food imports. European countries, which have been experiencing considerable declines in cropland, see relatively small growth in imports.

Looking specifically at forests, we plot growth rates in cropland and forest area at the country-level from 1960 to 2010 in figure SI 8.5. We see

a slight negative correlation, which aligns with the observation that cropland gains during the last century often came at the expense of forest land. This relationship holds for both temperate and tropical forest-dominated countries. We also plot the 1960 income tercile of each country, and see that richer countries tended to lose cropland (and lose relatively less forest), while poorer countries increased their cropland (and lost relatively more forest)—overall lending support to a tipping point in land use driven by economic development.

Finally, given the important role of policy in shaping land use decisions, as discussed earlier, we now analyze the relationship between one popular policy tool, agricultural subsidies, and cropland area growth. We use a measure from the World Bank's Relative Rate of Assistance (RRA) database (Anderson *et al* 2013). RRA is computed as:  $RRA = (1 + NRA_{agtrad}) / (1 + NRA_{nonagtrad}) - 1$ , where  $NRA_{agtrad}$  is the country-level subsidy rate of primary agricultural products (production-weighted by value) and  $NRA_{nonagtrad}$  is similarly the subsidy rate of the country's non-agricultural, tradable products. Therefore, a higher RRA implies that a country is subsidizing the agricultural sector relatively more and its non-agricultural sector.

Figure SI 8.6 plots country-level cropland area growth and average RRA from 1960 to 2010. Interestingly, we see a negative relationship, meaning that countries that subsidized agriculture more saw lower (or negative) cropland growth. This implies that such policies may even be used to mitigate cropland loss in places where it is already happening for the economic reasons we discuss in this paper.

#### 4. Discussion and conclusion

As agricultural land use has plateaued in recent decades, the loss of natural land in many regions has begun to reverse. These changes reflect a dimension of land use closely related to economic growth. In regions with incomes above \$5000 GDP per capita, economic growth is associated with more natural land. This tipping point dynamic is supported by both regression analysis and a Markov model analysis. Such an improved understanding of the income-land use dynamic can help inform conservation priorities, agricultural policy, as well as integrated climate models whose land use projections vary greatly based on the economic growth assumptions (Stehfest *et al* 2019).

Our findings contribute to the debate on how to meet the resource demands of a growing population that is getting richer (Sage 1994). Additional supplies of food and biomass can come from the intensive margin (i.e. increasing yields via crop genetics, agricultural inputs, mechanization, and irrigation) or the extensive margin (i.e. harvesting biomass from

virgin forests and converting them to agriculture) (Foley *et al* 2005, 2011, Rudel *et al* 2009, Burney *et al* 2010, Steinfeld and Gerber 2010, Tilman *et al* 2011). The extent to which food production will require conversion of additional natural lands to cultivation has important ecological, social, and economic implications.

The Borlaug hypothesis holds that increased yields stemming from improved crop technologies and intensification can produce the extra calories without requiring a major reduction in natural habitat (Borlaug 2007). The hypothesis has garnered some recent support (Stevenson *et al* 2013, Ramankutty *et al* 2018), but others contend that agricultural area must increase significantly to meet the needs of a growing global population (Tilman 1999, Alexandratos and Bruinsma 2012, Ray *et al* 2013, Laurance *et al* 2014, Molotoks *et al* 2018). Future work will be needed to reconcile these projected increases—ranging from 69 million hectares (Alexandratos and Bruinsma 2012) to 288 million hectares (Tilman 1999) in 2050—with the decrease in agricultural land we propose in this paper.

Our findings generally support the Borlaug hypothesis: cropland area has plateaued globally and across income group while crop production has continued to rise. However, such outcomes do not speak to intensive-extensive margin dynamics. The intensification-land-sparing theory, closely related to the Borlaug hypothesis, contends that rising yields should be accompanied by a decline in cultivated areas. Analyzing trends in corn, soybean, and wheat production, we see no obvious relationship in line with the findings of others (Rudel *et al* 2009). Yields increased greatly in nearly every country, but area under production was mixed. As such, there are many country-level examples that support intensification-land-sparing theory, and many that do not.

Declines in the agricultural footprint of rich countries may be enabled by imports from poor countries expanding their cropland area. Such shifts could be driven by trade in food products and globalization forces (Lambin and Meyfroidt 2011, Meyfroidt *et al* 2013). If such a 'land grab' hypotheses were true, we would expect greater increases in food imports in places that reduced their cropland area. However, we do not find evidence of such a relationship; if anything, we find a positive correlation in which countries simultaneously increase cropland area and food imports. Taken together, this evidence suggests that cropland change alone cannot explain the regime shift observed. Instead, the income-driven shift away from pastureland and growth in protected lands are important components.

Our findings also lend support to forest transition theory, which seeks to explain why countries go from net forest contraction to forest expansion. The theory is that forest transitions are driven by



farmers concentrating production among the most productive lands, resulting in the abandonment of formerly-farmed marginal lands which then regenerate to forest naturally or through tree crop planting (Mather and Needle 1998, Rudel *et al* 2005). In line with the literature, we observe forest transitions in much of Europe and North America (MacCleery 1993), and more recently in several developing countries, most notably China, where food production and forest cover simultaneously expanded (Lambin and Meyfroidt 2011). Our results also align with the increase in net tree cover observed at the global level (Song *et al* 2018). To the extent that agricultural intensification is related to economic growth, forest transition theory resembles a tipping point curve for deforestation in which forest cover would decline and then increase with a development (Cuaresma *et al* 2017).

Tropical forests, given their importance for biodiversity and as carbon sinks, deserve special attention. Our results show that while overall tropical forest loss has declined to historical lows, it has yet to fully plateau in low income countries, mainly in central Africa. We note that our dataset ends in 2010 following a period of declining Amazonian deforestation and strong economic growth; however, since 2010 deforestation has picked back up, returning to a rate of more than 10000 km yr<sup>-1</sup> in 2021 (Junior *et al* 2021). There is evidence that reductions in tropical deforestation can occur alongside increased agricultural production under the proper policy environment (Macedo *et al* 2012).

While many areas remain threatened by agricultural conversion, our findings suggest a reason to be optimistic about the prospects for natural ecosystems at a regional and global scale. National policies incentivizing smart agricultural planning and land conservation remain critical, but as more and more countries approach and pass an income threshold of \$5000 per capita, we anticipate reduced pressure to convert natural lands to cropland and a greater demand for natural amenities and protected lands.

### Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://drive.google.com/drive/folders/10nTV6jpiplnKZus61AH1zwDx4ScYM5LR>.

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### References

- Alexandratos N and Bruinsma J 2012 World agriculture towards 2030/2050: the 2012 revision *Technical Report*
- Andela N *et al* 2017 A human-driven decline in global burned area *Science* **356** 1356–62
- Andersen T, Carstensen J, Hernandez-Garcia E and Duarte C M 2009 Ecological thresholds and regime shifts: approaches to identification *Trends Ecol. Evol.* **24** 49–57
- Anderson K, Valenzuela E and Nelgen S 2013 Estimates of distortions to agricultural incentives, 1955–2011 *World Bank Report* WPS4612
- Ausubel J H, Wernick I K and Waggoner P E 2013 Peak farmland and the prospect for land sparing *Popul. Dev. Rev.* **38** 221–42
- Barrett J W 1994 *Regional Silviculture of the United States* (New York: Wiley)
- Barter P 2004 Transport, urban structure and 'lock-in' in the Kuala Lumpur metropolitan area *Int. Dev. Plan. Rev.* **26** 1–25
- Betts R A, Falloon P D, Goldewijk K K and Ramankutty N 2007 Biogeophysical effects of land use on climate: model simulations of radiative forcing and large-scale temperature change *Agric. For. Meteorol.* **142** 216–33
- Bodirsky B L and Müller C 2014 Robust relationship between yields and nitrogen inputs indicates three ways to reduce nitrogen pollution *Environ. Res. Lett.* **9** 111005
- Bolt J, Timmer M and van Zanden J L 2014 *How Was Life?: Global Well-being since 1820* OECD Publishing
- Borlaug N 2007 Feeding a hungry world *Science* **18** 359
- Bruner A G, Gullison R E, Rice R E and Da Fonseca G A 2001 Effectiveness of parks in protecting tropical biodiversity *Science* **291** 125–8
- Burney J A, Davis S J and Lobell D B 2010 Greenhouse gas mitigation by agricultural intensification *Proc. Natl Acad. Sci.* **107** 12052–7
- Conley T G 1999 GMM estimation with cross sectional dependence *J. Econom.* **92** 1–45
- Correa P and Schmidt C 2014 Public research organizations and agricultural development in Brazil: how did Embrapa get it right? *Technical Report*
- Cropper M and Griffiths C 1994 The interaction of population growth and environmental quality *Am. Econ. Rev.* **84** 250–4
- CRS 2021 *EU Agricultural Domestic Support: Overview and Comparison with the United States* vol **R46811** (Washington, DC: Congressional Research Service)
- Cuaresma J C, Danylo O, Fritz S, McCallum I, Obersteiner M, See L and Walsh B 2017 Economic development and forest cover: evidence from satellite data *Sci. Rep.* **7** 40678
- DeFries R S, Foley J A and Asner G P 2004 Land-use choices: balancing human needs and ecosystem function *Front. Ecol. Environ.* **2** 249–57
- Delang C O and Yuan Z 2016 *China's Grain for Green Program* (Berlin: Springer)
- Depauw L, Landuyt D, Perring M P, Blondeel H, Maes S L, Kopecký M, Máliš F, Vanhellemont M and Verheyen K 2019 A general framework for quantifying the effects of land-use history on ecosystem dynamics *Ecol. Indic.* **107** 105395
- Ellis E C, Klein Goldewijk K, Siebert S, Lightman D and Ramankutty N 2010 Anthropogenic transformation of the biomes, 1700 to 2000 *Glob. Ecol. Biogeogr.* **19** 589–606



- Feddema J J, Oleson K W, Bonan G B, Mearns L O, Buja L E, Meehl G A and Washington W M 2005 The importance of land-cover change in simulating future climates *Science* **310** 1674–8
- Foley J A *et al* 2005 Global consequences of land use *Science* **309** 570–4
- Foley J A *et al* 2011 Solutions for a cultivated planet *Nature* **478** 337–42
- Folke C, Carpenter S, Walker B, Scheffer M, Elmqvist T, Gunderson L and Holling C S 2004 Regime shifts, resilience and biodiversity in ecosystem management *Annu. Rev. Ecol. Evol. Syst.* **35** 557–81
- Frank E G and Schlenker W 2016 Balancing economic and ecological goals *Science* **353** 651–2
- Friedl M A, Sulla-Menashe D, Tan B, Schneider A, Ramankutty N, Sibley A and Huang X 2010 Modis collection 5 global land cover: algorithm refinements and characterization of new datasets *Remote Sens. Environ.* **114** 168–82
- Friedlingstein P *et al* 2019 Global carbon budget 2019 *Earth Syst. Sci. Data* **11** 1783–838
- Gasser T, Crepin L, Quilcaille Y, Houghton R A, Ciais P and Obersteiner M 2020 Historical CO<sub>2</sub> emissions from land use and land cover change and their uncertainty *Biogeosciences* **17** 4075–101
- Geoghegan J, Pritchard L, Ogneva-Himmelberger Y, Chowdhury R R, Sanderson S and Turner B 1998 “Socializing the pixel” and “pixelizing the social” in land-use and land-cover change *People and Pixels* (Washington, DC: National Academy Press)
- Grau H R, Aide T M, Zimmerman J K, Thomlinson J R, Helmer E and Zou X 2003 The ecological consequences of socioeconomic and land-use changes in postagriculture Puerto Rico *BioScience* **53** 1159–68
- Grossman G M and Krueger A B 1995 Economic growth and the environment *Q. J. Econ.* **110** 353–77
- Harris J R and Todaro M P 1970 Migration, unemployment and development: a two-sector analysis *Am. Econ. Rev.* **60** 126–42
- Houghton R A 2008 Carbon flux to the atmosphere from land-use changes: 1850–2005 *Technical Report*
- Houghton R 1999 The annual net flux of carbon to the atmosphere from changes in land use 1850–1990 *Tellus B* **51** 298–313
- Hurt G C *et al* 2011 Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest and resulting secondary lands *Clim. Change* **109** 117–61
- Hurt G C *et al* 2020 Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6 *Geosci. Model Dev.* **13** 5425–64
- Inkelaar R, de Jong H, Bolt J and van Zanden J 2018 *GGDC Research Memorandum* GD-174 Groningen Growth and Development Centre, University of Groningen
- Irwin E G and Geoghegan J 2001 Theory, data, methods: developing spatially explicit economic models of land use change *Agric. Ecosyst. Environ.* **85** 7–24
- Jacobsen J B and Hanley N 2009 Are there income effects on global willingness to pay for biodiversity conservation? *Environ. Resour. Econ.* **43** 137–60
- Junior C H S, Pessôa A C, Carvalho N S, Reis J B, Anderson L O and Aragão L E 2021 The Brazilian Amazon deforestation rate in 2020 is the greatest of the decade *Nat. Ecol. Evol.* **5** 144–5
- Klein Goldewijk K, Beusen A, Doelman J and Stehfest E 2017 New anthropogenic land use estimates for the holocene: HYDE 3.2 *Earth Syst. Sci. Data* **9** 927–53
- Klein Goldewijk K, Beusen A and Janssen P 2010 Long-term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1 *Holocene* **20** 565–73
- Klein Goldewijk K, Beusen A, Van Dreht G and De Vos M 2011 The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years *Glob. Ecol. Biogeogr.* **20** 73–86
- Koop G and Tole L 1999 Is there an environmental Kuznets curve for deforestation? *J. Dev. Econ.* **58** 231–44
- Kopp R E, Shwom R L, Wagner G and Yuan J 2016 Tipping elements and climate–economic shocks: pathways toward integrated assessment *Earth's Future* **4** 346–72
- Krausmann F, Erb K-H, Gingrich S, Haberl H, Bondeau A, Gaube V, Lauk C, Plutzer C and Searchinger T D 2013 Global human appropriation of net primary production doubled in the 20th century *Proc. Natl Acad. Sci.* **110** 10324–9
- Kuznets S 1955 Economic growth and income inequality *Am. Econ. Rev.* **45** 1–28
- Lambin E F *et al* 2001 The causes of land-use and land-cover change: moving beyond the myths *Glob. Environ. Change* **11** 261–9
- Lambin E F and Meyfroidt P 2011 Global land use change, economic globalization and the looming land scarcity *Proc. Natl Acad. Sci.* **108** 3465–72
- Laurance W F, Sayer J and Cassman K G 2014 Agricultural expansion and its impacts on tropical nature *Trends Ecol. Evol.* **29** 107–16
- Lenton T M, Rockström J, Gaffney O, Rahmstorf S, Richardson K, Steffen W and Schellnhuber H J 2019 Climate tipping points—too risky to bet against *Nature* **575** 592–5
- Lewis W A 1954 Economic development with unlimited supplies of labour *Manchester Sch.* **22** 139–91
- Lippman T W 2010 Saudi Arabia's quest for “food security” *Middle East Policy* **17** 90
- Liu X, Yu L, Si Y, Zhang C, Lu H, Yu C and Gong P 2018 Identifying patterns and hotspots of global land cover transitions using the ESA CCI land cover dataset *Remote Sens. Lett.* **9** 972–81
- Lowder S K, Skoet J and Raney T 2016 The number, size and distribution of farms, smallholder farms and family farms worldwide *World Dev.* **87** 16–29
- MacCleery D W 1993 *American Forests: A History of Resiliency and Recovery* (Washington, DC: U.S. Department of Agriculture, Forest Service)
- Macedo M N, DeFries R S, Morton D C, Stickler C M, Galford G L and Shimabukuro Y E 2012 Decoupling of deforestation and soy production in the southern amazon during the late 2000s *Proc. Natl Acad. Sci.* **109** 1341–6
- Mather A S and Needle C 1998 The forest transition: a theoretical basis *Area* **30** 117–24
- McClintock B T, Langrock R, Gimenez O, Cam E, Borchers D L, Glennie R and Patterson T A 2020 Uncovering ecological state dynamics with hidden Markov models *Ecol. Lett.* **23** 1878–903
- Meiyappan P and Jain A K 2012 Three distinct global estimates of historical land-cover change and land-use conversions for over 200 years *Front. Earth Sci.* **6** 122–39
- Meyfroidt P, Lambin E F, Erb K-H and Hertel T W 2013 Globalization of land use: distant drivers of land change and geographic displacement of land use *Curr. Opin. Environ. Sustain.* **5** 438–44
- Milchunas D G and Lauenroth W K 1993 Quantitative effects of grazing on vegetation and soils over a global range of environments *Ecol. Monogr.* **63** 327–66
- Milkoreit M *et al* 2018 Defining tipping points for social-ecological systems scholarship—an interdisciplinary literature review *Environ. Res. Lett.* **13** 033005
- Molotok A, Stehfest E, Doelman J, Albanito F, Fitton N, Dawson T P and Smith P 2018 Global projections of future cropland expansion to 2050 and direct impacts on biodiversity and carbon storage *Glob. Change Biol.* **24** 5895–908
- Mustard J F, Defries R S, Fisher T and Moran E 2012 Land-use and land-cover change pathways and impacts *Land Change Science* (Berlin: Springer) pp 411–29
- Pekel J-F, Cottam A, Gorelick N and Belward A S 2016 High-resolution mapping of global surface water and its long-term changes *Nature* **540** 418–22

- Popp A *et al* 2017 Land-use futures in the shared socio-economic pathways *Glob. Environ. Change* **42** 331–45
- Queiroz C, Beilin R, Folke C and Lindborg R 2014 Farmland abandonment: threat or opportunity for biodiversity conservation? A global review *Front. Ecol. Environ.* **12** 288–96
- Ramankutty N, Evan A T, Monfreda C and Foley J A 2008 Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000 *Glob. Biogeochem. Cycles* **22** GB1003
- Ramankutty N and Foley J A 1999 Estimating historical changes in global land cover: croplands from 1700 to 1992 *Glob. Biogeochem. Cycles* **13** 997–1027
- Ramankutty N, Mehrabi Z, Waha K, Jarvis L, Kremen C, Herrero M and Rieseberg L H 2018 Trends in global agricultural land use: implications for environmental health and food security *Annu. Rev. Plant Biol.* **69** 789–815
- Ranis G and Fei J C 1961 A theory of economic development *Am. Econ. Rev.* **51** 533–65
- Ray D K, Mueller N D, West P C and Foley J A 2013 Yield trends are insufficient to double global crop production by 2050 *PLoS One* **8** e66428
- Reyna J L and Chester M V 2015 The growth of urban building stock: unintended lock-in and embedded environmental effects *J. Ind. Ecol.* **19** 524–37
- Rudel T K *et al* 2009 Agricultural intensification and changes in cultivated areas, 1970–2005 *Proc. Natl Acad. Sci.* **106** 20675–80
- Rudel T K, Bates D and Machinguishi R 2002 A tropical forest transition? Agricultural change, out-migration and secondary forests in the Ecuadorian Amazon *Am. Assoc. Am. Geogr.* **92** 87–102
- Rudel T K, Coomes O T, Moran E, Achard F, Angelsen A, Xu J and Lambin E 2005 Forest transitions: towards a global understanding of land use change *Glob. Environ. Change* **15** 23–31
- Runyan C and D’Odorico P 2016 *Global Deforestation* (Cambridge: Cambridge University Press)
- Sage C 1994 Population and income *Changes in Land Use and Land Cover: A Global Perspective* vol 263 (New York: Cambridge University Press) p 285
- Sanderson E W, Jaiteh M, Levy M A, Redford K H, Wannebo A V and Woolmer G 2002 The human footprint and the last of the wild: the human footprint is a global map of human influence on the land surface, which suggests that human beings are stewards of nature, whether we like it or not *BioScience* **52** 891–904
- Scheffer M *et al* 2009 Early-warning signals for critical transitions *Nature* **461** 53–59
- Smith P *et al* 2013 How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Glob. Change Biol.* **19** 2285–302
- Song X-P, Hansen M C, Stehman S V, Potapov P V, Tyukavina A, Vermote E F and Townshend J R 2018 Global land change from 1982 to 2016 *Nature* **560** 639–43
- Specht J 2019 *Red Meat Republic: A Hoof-to-Table History of How Beef Changed America* (Princeton, NJ: Princeton University Press)
- Stehfest E *et al* 2019 Key determinants of global land-use projections *Nat. Commun.* **10** 2166
- Steinfeld H and Gerber P 2010 Livestock production and the global environment: consume less or produce better? *Proc. Natl Acad. Sci.* **107** 18237–8
- Stevenson J R, Villoria N, Byerlee D, Kelley T and Maredia M 2013 Green revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production *Proc. Natl Acad. Sci.* **110** 8363–8
- Tilman D 1999 Global environmental impacts of agricultural expansion: the need for sustainable and efficient practices *Proc. Natl Acad. Sci.* **96** 5995–6000
- Tilman D *et al* 2001 Forecasting agriculturally driven global environmental change *Science* **292** 281–4
- Tilman D, Balzer C, Hill J and Befort B L 2011 Global food demand and the sustainable intensification of agriculture *Proc. Natl Acad. Sci.* **108** 20260–4
- Tscharntke T, Clough Y, Wanger T C, Jackson L, Motzke I, Perfecto I, Vandermeer J and Whitbread A 2012 Global food security, biodiversity conservation and the future of agricultural intensification *Biol. Conserv.* **151** 53–59
- Turner B L and Meyer W B 1994 Global land-use and land-cover change: an overview *Changes in Land Use and Land Cover: A Global Perspective* vol 4 (Cambridge: Cambridge University Press)
- UNECE 1996 *Long-Term Historical Changes in the Forest Resource* (Geneva: United Nations)
- UNEP-WCMC, IUCN 2018 *Protected Planet: The World Database on Protected Areas (Wdpa)* vol 21 (Cambridge: UNEP-WCMC and IUCN) (available at: [www.protectedplanet.net](http://www.protectedplanet.net))
- UNEP 2002 *Global Environmental Outlook: 3, Past, Present and Future Perspectives* (London: Earthscan Publications)
- Usher M 1981 Modelling ecological succession, with particular reference to Markovian models *Vegetation Dynamics in Grasslands, Heathlands and Mediterranean Ligneous Formations* (Berlin: Springer) pp 11–18
- Van Ginkel K C *et al* 2020 Climate change induced socio-economic tipping points: review and stakeholder consultation for policy relevant research *Environ. Res. Lett.* **15** 023001
- Vitousek P M, Mooney H A, Lubchenco J and Melillo J M 1997 Human domination of earth’s ecosystems *Science* **277** 494–9
- Williams M 1992 *Americans and Their Forests: A Historical Geography* (Cambridge: Cambridge University Press)