Consequences of agricultural total factor productivity growth for the sustainability of global farming: accounting for direct and indirect land use effects

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Abstract
Most of the growth in agricultural output in the last thirty years comes from increases in the efficiency with which both land and non-land inputs are used. Recent work calls for a better understanding of whether this efficiency, known as total factor productivity (TFP), contributes to a more sustainable food system. Key to this understanding is the documented phenomenon that, instead of saving lands, the introduction of technologies that improve agricultural productivity encourage cropland expansion. We extend the results of a recently published econometric model of cross-country cropland change and TFP growth to explore the extent to which improvements in technology were associated with lower greenhouse emissions from land conversion to agriculture as well as with lower land conversion pressures in biodiversity-rich biomes. We focus on the decade of 2001–2010, a period in which our sample of 70 countries (≈75% of global croplands) experienced net land contraction. Except in sub-Saharan Africa and South and East Asia, regional TFP growth was associated with regional land expansion, thus confirming the existence of Jevons paradox in most regions of the world. However, such expansion was more than offset by indirect land use effects stemming from increases in productivity somewhere else. These indirect effects are far from trivial. In the absence of TFP growth, our estimates suggest that ≈125 Mha would have been needed to satisfy demand, half of which are in the four most biodiverse biomes of the world; estimated land use emissions from the ensuing changes in land use range from a lower bound of 17 Gt CO2eq to an upper bound of 84 Gt CO2eq, depending on whether the expansion would have occurred on pasturelands or forest, in contrast to the ≈1 to 15 Gt CO2eq imputed to observed cropland expansion. Our projections of the land needed to satisfy projected growth in TFP per capita during 2018–2023 indicate that current rates of TFP growth are insufficient to prevent further land expansion, reversing in most cases the in-sample trends in land contraction observed during 2001–2010.

1. Introduction
The social and environmental trade-offs between input intensification and land extensification are central to the debates about how to increase the sustainability of global farming (Phalan and Green 2016, Balmford et al 2018, Pretty et al 2018). Such focus obscures the fact that most of the growth in agricultural output in the last thirty years is not explained by either of these processes, but rather from increases in the efficiency with which both land and non-land inputs are used (Ruttan 2002, Fuglie 2012, Baldos and Hertel 2016, Heisey and Fuglie 2018, Searchinger et al 2018, Coomes et al 2019). Such efficiency, known as total factor productivity (TFP), is distinct from input intensification insofar as input intensification increases yields by using more non-land inputs, such as fertilizers or water, but it is not tied to gains in the efficiency with which resources are used. TFP growth is important for both economy-wide and agricultural growth. Between a quarter and third of...
the output per worker in industrialized countries comes from TFP growth (Baier et al. 2007). In the case of agriculture, starting in the 1990s, TFP growth outpaced input use as the main source of agricultural growth, explaining about three-quarters of global agricultural growth and almost all the agricultural growth in industrialized countries (Fuglie 2012, 2015).

TFP is defined as the ratio of output to inputs (Hulten 2001, p 10). A common way of measuring TFP growth—i.e. the rate at which the ratio of outputs to inputs changes over time—is to take the difference between the growth rate of output and the growth rate of input use (Ruttan 2002). In other words, TFP growth is the ‘residual’ growth in output that cannot be accounted for by growth in input use (Hulten 2001). For instance, if all the changes in production were due to greater input use (e.g. more fertilizers, workers, and/or land), the change in TFP would be zero. Conversely, when output grows faster than the use of inputs required for production, the difference between the two is interpreted as a change in the productivity of all the factors employed in production.

TFP growth captures factor-neutral technological change, whereby the productivity of all inputs rises simultaneously and in the same proportion. So, a 1% increase in TFP implies a 1% increase in output after adjusting for changes in input use. However, factor-biased technological change—such as the introduction of labor-saving machinery that may facilitate clearing forested land (e.g. Maertens et al. 2006), or the adoption of land-saving but labor-intensive technologies (e.g. the application of fertilizer and chemicals for plant control) —is pervasive in agriculture (Ruttan 2002, Gallardo and Sauer 2018). The adoption of these technologies increases output beyond what would be expected from input intensification, while simultaneously changing the mix of the inputs used in production. In the presence of factor-biased technical change, TFP indices calculated as residuals embed the output-enhancing effect of the improved inputs, while the changes in the input mix are captured by the growth rates of input use (for a formal argument, see Hulten 2001, p 10).

TFP growth arises because of technical change and improvements in efficiency. The introduction of improved plant varieties more responsive to technical inputs and management, along with greater input intensification, advances in agricultural mechanization and substantial expansion of irrigated agriculture combine to enhance the productivity of land and labor (Ruttan 2002). The development and adoption of these technologies requires substantial investments on physical and human capital (Evenson and Fuglie 2010). Patterns of international specialization as well as economies of scale due to access to larger markets are also important determinants of TFP growth and its diffusion (Fuglie 2017b).

As a consequence, wide disparities exist in the levels of agricultural productivity across countries. A non-exhaustive review of the literature suggests that agricultural TFP is higher in countries with higher expenditures on R&D (Evenson and Fuglie 2010, Fuglie 2017a), higher levels of educational attainment (Reimers and Klasing 2013), better access to modern inputs (Craig et al. 1997, Restuccia et al. 2008), lower agricultural price distortions due to trade restrictions (Fulghini and Perrin 1993, Tombe 2015), better infrastructure (Antle 1983, Craig et al. 1997), less unequal land distribution (Vollrath 2007), and more flexible labor markets (Restuccia et al. 2008).

Recent work seeks to widen the scope of the debate about the strategies needed to achieve sustainable farming by better understanding the role of TFP growth on land use. For instance, Searchinger et al. (2018) note that research and development geared toward achieving TFP growth is the single most important strategy to compensate future increases in demand for agricultural goods in the face of losses in productivity from climate change as well as increases in population and income growth; a proposition that is largely missed in the influential assessments from the Intergovernmental Panel on Climate Change (Searchinger et al. 2018, p 22). More generally, Coomes et al. (2019) highlights the need to understand whether TFP growth contributes to a more sustainable food system. Key to this understanding is the so-called ‘Jevons paradox’ (Alcott 2005). This paradox states that, instead of saving lands, the introduction of technologies that improve agricultural productivity can actually encourage the expansion of agricultural lands, as documented by, for example, Angelsen and Kaimowitz (2001), Ceddia et al. (2013), and Phalan and Green (2016).

By definition, TFP growth implies an increase in the amount of agricultural products and a reduction of agricultural prices (e.g. Helmerberger and Chavas 1996, pp 115–7). The key determinant of the rate at which prices adjust to changes in supply is the elasticity (or slope) of the excess demand function. This elasticity depends on both domestic and foreign demand conditions, as well to the ability of foreign producers to adapt to changes in market prices. Conceptually, it is well understood that TFP growth will translate into land expansion if the reduction in agricultural prices is less than proportional to the increase in production (Helmerberger and Chavas 1996, Angelsen and Kaimowitz 2001, Hertel et al. 2014). Such a situation, captured by an elastic excess demand for farm products, contrasts with an inelastic excess demand whereby prices respond more than proportionally to changes in production. When excess demand is inelastic, the faster reduction in prices relative to increases in production reduces farmers’ revenues, triggering a reduction in the amount of land (and other farm owned inputs) that farmers are willing to supply to the productive process (Helmerberger and Chavas 1996, p 116). The degree of market integration of a productive region with other regions is a main determinant of the elasticity of excess demand (Hertel et al. 2014).

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2 This method is known as growth accounting. Other methods include econometric estimation of production functions and distance-based approaches (Zeppeda 2001, Headey et al. 2010).
For example, the increase in production following the adoption of a new seed in a village that is disconnected from outside markets will cause farmers to reduce planting in the face of lower prices. However, in a village well connected to other markets so that its producers are a small fraction of all existing producers, it is likely that market prices are insensitive to increases in production, which improves the profitability of agriculture, thus stimulating cropland expansion.

This implies that TFP growth in regions that are well connected to world markets and produce commodities that are heavily traded is likely to lead to further land expansion. In recent work, regression estimates from Villoria (2019) suggest that, given the levels of international trade during 2001–2010, there are relatively few regions in the world (some countries in sub-Saharan Africa and South and East Asia) where increases in TFP during this period resulted in cropland reduction. Yet, the story of how TFP growth helps to conserve global lands is more nuanced. In an tightly interlinked world, increases in productivity in a given region may displace other competitors in world markets, therefore, alleviating pressures for deforestation elsewhere. As discussed below, the international changes in land use associated with domestic TFP growth are far from trivial, and in some cases as important as TFP-driven changes in domestic land use.

In this context, this article has three objectives. The first objective is to shed light on the seeming paradox contradiction whereby TFP-driven land expansion at the country level results in TFP-driven global land savings. The second objective is to explore whether the geographic patterns of TFP growth in the recent past were conducive to improve two key indicators of global sustainability, namely greenhouse gas (GHG) emissions and biodiversity. We do this by translating counterfactual estimates of the cropland that would have been needed to satisfy observed demand into GHG emissions and also by mapping these counterfactual land needs onto ecoregions, a procedure that gives a first approximation to understanding the implications of spatially heterogeneous patterns of TFP growth for biodiversity richness. We focus on the period 2001–10, a period in which global cropland contracted for the countries under analysis, which covered close to 75% of the global cropland (see observed changes during 2001–2010 in figure 1; included countries are listed in figure S-4, available online at stacks.iop.org/ERL/14/125002/mmedia). The third objective is to explore whether current rates of TFP growth are enough to counteract the relatively short-term rates of demand implied by projections of population and GDP per capita growth to 2025.

2. Methods

Our starting point is the model of cropland expansion developed by Villoria (2019). This model explicitly recognizes that land supply decisions in one location are intertwined with cropland decisions elsewhere as producers from different countries compete among themselves in order to supply domestic and foreign markets. The model focuses on TFP-driven price differentials. Specifically, a uniform increase in the productivity of all the inputs employed in the production process, or TFP growth, reduces the costs of production, which in turn allows the producers that enjoy the innovation to charge a lower price compared to their competitors. By charging a lower price, the innovating country can capture a larger market share in the destination market, thus displacing other producers. The displaced producers, in turn, are forced to reduce their levels of supply, reducing the pressures to expand on cropland.

Empirically, the changes in output prices received by farmers can be decomposed into TFP growth and the weighted changes in land and non-land input prices, using as weights the shares of each input on total production costs (SM S-1). This allows for a direct link between growth rates in national cropland in country i at time t, denoted by $l_{it}$, on the one hand, to growth rates of both domestic and foreign TFP growth ($tfp_{it}$ and $tfp_{jt}$), on the other hand. The theory behind the regression model suggests holding constant other key determinants of the supply and demand of cropland.

In addition to TFP growth, the regression includes the growth rate of the price of non-land inputs, using growth in fertilizer prices ($fert$) as a proxy, as well growth rates of land rents ($rent$), both domestic and foreign. On the demand side, this letter extends the regression model in Villoria (2019) by separating domestic from foreign demand, as captured by growth in GDP per capita (gdpcap$_p$ and gdpcap$_{p,i}$). We also control for population growth ($pop$). Changes in trade policy are captured by including changes in the bilateral trade costs that two competitors $i$ and $k$ face in a third market $j$ ($tcost_{ij}$ and $tcost_{jk}$). Using $\mu_{it}$ to denote country fixed effects, and $\varepsilon_{it}$ to denote model residuals, assumed to be uncorrelated with the other terms on the right hand side of the regression, the extended version of the regression model is given by:

$$l_{it} = \beta_1 tfp_{it} + \beta_2 \sum_{k=1}^{n} \omega_{ik} (tfp_{kt} - tfp_{it})$$

$$+ \beta_3 \gamma_{ii} \text{gdpcap}_{it} + \beta_4 \sum_{j=1}^{n} \gamma_{ij} \text{gdpcap}_{jt}$$

$$+ \beta_5 \text{fert}_{it} + \beta_6 \sum_{k=1}^{n} \omega_{ik} (rent_{it} - rent_{kt})$$

$$+ \beta_7 \sum_{k=1}^{n} \omega_{ik} (fert_{it} - fert_{kt})$$

$$+ \beta_8 \sum_{k=1}^{n} \sum_{j=1}^{m} \gamma_{ij} \delta_{kj} (tcost_{ij} - tcost_{jk})$$

$$+ \beta_9 \text{SUITL}_i + \beta_{10} \text{pop}_it + \varepsilon_{it}. \quad (1)$$

The parameters $\beta_1$ and $\beta_2$ measure the sensitivity of cropland growth to domestic TFP growth. This
sensitivity depends on $\omega_{ikt}$, which is a competition index that measures the exposure of producers in country $i$ to competition with producers in country $k$, at a time $t$. To illustrate the forces captured by $\omega_{ikt}$, consider the competition between US and Argentina’s farmers in Japan’s market (figure S-1). From the perspective of US producers, such competition can be summarized by the product of two terms. First, the share of total US agricultural sales that are sold in Japan determine how exposed US farmers are to changes in competition conditions in the Japanese market. We refer to these shares as revenue shares, and they are denoted by $\gamma_{ij}$ (where, in this instance, $i = \text{US}$ and $j = \text{Japan}$). The second term reflects how much of Japan’s total consumption bill is spent on goods originated in Argentina. We refer to these shares as Japan’s budget shares, and denote them by $\delta_{kj}$ (in this example, $j = \text{Japan}$ and $k = \text{Argentina}$). Exposure of US producers to competition with Argentina’s producers in Japan is given by the bilateral competition index $\gamma_{US,Japan} \times \delta_{Argentina,Japan}$. So, for any level of the share of Japan’s market in US total sales, the larger the budget share that Japan devotes to Argentina’s imports, the larger the exposure of US producers to changes in the competitiveness of Argentina’s producers. By summing the bilateral competition indices between

**Figure 1.** Changes in cropland (A) and GHG emissions (B). Note: In (A), error bars are simulated standard deviations of prediction intervals following (Gelman and Hill 2007, pp 140–4). In (B) the ends of the error bars are the lower (all cropland expansion comes from pastures) and upper (all the conversion takes place in forests) bounds of GHG emissions; the height of the bar is the average of these two values. Source: Observed Cropland is from FAOSTAT. The rest are own calculations based on parameter estimates in SM S-3.
the US and Argentina across the markets where they compete, we have a measure of the aggregated competition that US producers face from Argentina’s producers, we denote these as ω_k = US,k = Argentina.

Formally, the marginal effect of domestic TFP growth is given by:

$$\frac{∂τ_i}{∂t_{FPi}} = β_1 - β_2 \sum_{k=1}^{n} ω_{ik}.$$  

(2)

Villoria (2019) shows that β_1 < 0, which implies that for a fully isolated country—where ω_k = 0 for all the potential competing countries indexed by k—TFP growth reduces cropland expansion. Moreover, β_2 < 0, therefore, as farmers get more exposed to competition from abroad, so the term ∑_{k=1}^{n} ω_{ik} gets larger, the second term in the right hand side of equation (2) counteracts the saving effect of cropland of domestic TFP growth. As discussed in the results, for most countries, current levels of ∑_{k=1}^{n} ω_{ik} tend to be large enough that TFP growth is actually associated with cropland expansion—the situation known as Jevons paradox. SM-S-4 shows that equation (2) is closely related to the excess demand elasticity; this fact is what allows equation (2) to parsimoniously discern between whether TFP growth is associated with cropland savings or cropland expansion.

Another useful result from equation (1) is that the indirect land use effect of foreign TFP growth can be readily estimated as the marginal effect of foreign TFP growth, t_{FPi}, on domestic cropland growth:

$$\frac{∂τ_i}{∂t_{FPi}} = β_2 ω_{ik}, \quad β_2 < 0.$$  

(3)

That is, the larger the exposure of farmers in country i to the farmers in country k, the larger the reduction in their cropland as a response to technological improvements in country k. The competition indices are dynamic entities that change as countries enter into trade agreements or deepen their commercial commitments as part of World Trade Organization’s Agreement on Agriculture. Indeed, over the last three decades, most countries have experienced an increase in their competition indices (figures S-2 and S-3), a fact that reflects increased globalization of world agricultural trade (OECD/FAO 2017).

The parameter estimates of equation (1) are used to estimate the contributions of both domestic and foreign TFP and per capita GDP growth, as well as population growth, to the change in hectares during 2001–2010. For this, for each country, the independent variables in the left hand side of equation (1) are divided by the fitted cropland growth rate during 2001–10, ̄τ_{2001–2010}, when multiplied by 100, these are the percent contribution of each source of cropland growth to the fitted cropland growth rates. These shares are used to determine the share of hectares that are attributable to each source of growth. The fitted cropland growth rates are translated into hectares by multiplying observed cropland hectares in 2001 from FAOSTAT (I_{2001}) times the percentage change in cropland between 2001 and 2010 implied by the fitted cropland growth rates, ̄τ_{2001–2010}, i.e. cropland in 2010 equals \(L_{2001} \times \exp(̄τ_{2001} \times T),\) where T = 9 are the years between 2001 and 2010:

$$ΔA_{area, 2001–2010} = L_{2001} \times \exp(̄τ_{2001} \times T) - L_{2001}.$$  

(4)

In the section Results, we use the parameter estimates of equation (1) to examine counterfactual changes in cropland composition under the assumption of zero TFP growth during 2001–2010 as well as projections of population and GDP per capita to 2025.

### 2.1. GHG emissions

Emissions from TFP-driven changes in cropland area are calculated using the Agro-ecological Zone Emission Factor (AEZ-EF) Model (Plevin et al 2014). The AEZ-EF model closely follows IPCC GHG inventory methods and relies on its default values. The model includes cover-specific (cropland, pastures and forests) subnational carbon estimates for biomass (above- and below-ground), dead organic matter, and soil carbon from Gibbs et al (2014). It also includes data on carbon remaining on harvested wood products, non-CO2 emissions, and foreground sequestration. The carbon stock data is combined with assumptions about carbon sequestration from forest growth (foreground if converted), mode of conversion and CO2 emissions from land clearing using fire, and the fraction of carbon that remains sequestered in wood products during a 30 year time horizon. The AEZ-EF model is designed to estimate land use emissions from land use transitions predicted by comparative static economic models, whereby one starts with a baseline and estimates the resulting final equilibrium, which are the type of counterfactuals in the current letter. The AEZ-EF model underlies the emission estimates in several analysis of the indirect land use effects of biofuels (e.g. Taheripour et al 2017).

A caveat of our approach, is that it does not allow to identify the sources of cropland expansion or the type of cover to which cropland reverts in the case of cropland contraction. To bound the uncertainty regarding land use transition, we consider two scenarios. One scenario assumes that all the cropland is coming from the conversion of pastures. This can be considered a lower bound estimate of the relevant GHG emissions. The other scenario is an upper bound that assumes that all the land is coming from the conversion of forests. We also report the average of these two values.

### 2.2. Biodiversity

We assume that cropland expanded in the ecoregions of each country at the observed or counterfactual rates that we obtain from each country. This provides a
perspective on the location of actual and counterfactual land savings and species richness. For this, spatially explicit data on cropland (Goldewijk et al. 2010, 2011) was merged with data on species richness (birds, amphibians, and mammals) (Jenkins et al. 2013, Pimm et al. 2014), and then aggregated to the 827 global ecoregions (Olson et al. 2001). Once the country-level changes in cropland area are applied to the ecoregions, we aggregate them to 14 global biomes as described by Olson et al. (2001).

3. Results

Equation (1) is estimated using a two-period panel (growth rates during 1991–2000 and during 2001–2010), for 70 countries that represent around 75% of global cropland. Data sources and variable construction are discussed in SM S-1. All the specifications (shown in SM S-3) include country fixed effects. A strong body of evidence points out to agricultural TFP being mainly the inertial product of investments in agricultural R&D with significant time lags, ranging from 20 to 50 years from initial investments to actual productivity gains (Fuglie 2017a). In this sense, TFP growth can be considered exogenous to contemporaneous cropland expansion. Yet, policies that help to broaden the adoption of technology may operate in shorter time frames, introducing the possibility that the estimates of \( \beta_1 \) and \( \beta_2 \) confound the effect of TFP growth with the effects of the enabling policies. Another important concern in estimating equation (1) is that cropland growth is a component of the aggregated input growth used to calculate the TFP terms. This introduces an obvious dependence between the indices of TFP growth and the error terms, e.g. a positive shock to \( \varepsilon_{it} \) will affect cropland growth, which will affect the measure of TFP growth.

Villoria (2019) explores the potential consequences of simultaneous equation bias and other sources of endogeneity by using past expenditures (20 years lag) in agricultural research and development from (Fuglie 2017a) as instrumental variables (IV) for contemporaneous TFP growth. Relative to the ordinary least squares (OLS) estimates, the IV estimates indicate what are probably implausibly large land saving effects of TFP growth on cropland expansion (SM S-3). This, along unresolved concerns about the use of F-tests for detecting instrument strength (Young 2017) suggests to err on the side of caution and use the downward (relative to IV) biased OLS estimates (SM S-3).

In the long-run, investments in R&D, and the ensuing growth in TFP, are influenced by relative factor scarcity (Ruttan 2002); to account for the possibility that historically land constrained countries may display high rates of TFP growth without significant changes in their cropland area, we control for the share of suitable land for agriculture that is under cropland in each decade. An additional factor conditioning land scarcity are environmental policies that impose farming restrictions. Comprehensive and consistent time-series of changes in these policies at the country level are difficult to obtain. Nevertheless, results reported in Villoria (2019) find that the parameter estimates were robust to participation in REDD (Reducing Emissions from Deforestation and Degradation), changes in the number of REDD projects, as well as to changes in the share of the territory under protected areas.

3.1. Indirect land use effects dominate domestic effects

Figure 2 decomposes changes in regional cropland between 2001 and 2010 into the contributions of regional and extra-regional growth in TFP, population growth, and regional and extra-regional GDP per capita. The displayed changes in cropland are obtained from regression fitted values as explained in SM-S-1. Four empirical patterns are worth highlighting. First, population growth has a positive effect on cropland expansion in all the regions. Second, after correcting for population growth, only in Developing Asia (developing countries in South and East Asia) and sub-Saharan Africa, the growth in regional demand, as captured by growth in GDP per capita, dominates extra-regional demand as a source of land expansion. Such dominance of regional demand over foreign demand is consistent with the fact that the countries in these regions tend to have the lowest exposure to international trade (SM S-3). In sharp contrast, the single most important source of cropland expansion in both South America and Southeast Asia—as well as in Canada and the US, Europe, and Oceania—is growth in extra-regional GDP per capita, supporting the observation that a considerable amount of land conversion has been a response to a greater demand for exports (see e.g. DeFries et al. 2010, Yu et al. 2013).

Third, again with the exception of Developing Asia and sub-Saharan Africa, regional TFP growth was associated with regional land expansion. In Latin America and Southeast Asia, the expansion of cropland due to regional TFP growth is as large as the expansion of cropland used to satisfy regional demand. In Canada and the US, TFP-driven expansion dwarfs the contribution of growth in regional demand. For individual farmers in these regions, their market is the world. As a consequence, increases in production due to improved TFP have, if any, a lesser than proportional downward pressure on world prices. When production increases at a faster rate than the corresponding fall in prices, regional agriculture becomes more profitable, thereby enticing expansion into new croplands. By contrast, in many places in Developing Asia and sub-Saharan Africa, farmers are still relatively isolated from world markets making regional prices to fall by a larger proportion than the increases in regional output stemming from growth in regional TFP. In other words, at least during 2001–2010, producers in these regions faced an
inelastic regional excess demand for agricultural products, whereby TFP growth is associated with reduced revenues due to the price depressing effect of increased output. As it is natural, the aggregation from countries to regions masks important differences. For instance, large commodity exporters are highly integrated into world markets, and are more prone to experience Jevons’ paradox—for instance, figure S-3 shows that the competition index of Ivory Coast is on par with the largest commodity exporters (relative to their domestic sectors) in South America, i.e. Argentina and Uruguay. However, in most countries within sub-Saharan Africa, most competition indices are still below those in other regions.

The fourth, and most striking pattern, is that—again, with the exception of Developing Asia and sub-Saharan Africa—extra-regional TFP growth was a powerful source of land savings, in most cases fully offsetting the cropland expansion needed to satisfy both regional and extra-regional demand growth. These extra-regional land use effects reconcile TFP-driven regional cropland expansion (Jevons paradox) with TFP-driven global land savings.

To appreciate the importance of the indirect (extra-regional) land use effects in the accounting of the effects of TFP growth in land use, figure 3 shows that these tend to overcome the direct (regional) land expansion effects. For example, the global land savings
attributable to TFP growth in the US and Canada, around 35 million hectares (Mha) in 2001–10, more than compensated the land expansion in the region (≈18 Mha) that would be attributable to regional TFP growth. Similarly, although TFP growth in Latin America and Southeast Asia was associated with the incorporation of ≈9 Mha and ≈4 Mha, regional increases in productivity reduced land needs elsewhere by ≈22 Mha and ≈10 Mha, respectively.

3.2. TFP growth during 2001–2010 restrained cropland expansion in the sample countries
The decomposition above offers insights into how Jevons paradox in some regions is consistent with global land saving effects originated in TFP growth. A different question, however, is whether TFP growth had the effect of saving land, even in those regions that are prone to Jevons paradox. In other words, would have technological stagnation resulted in less cropland expansion all across the world? For this we use the parameter estimates in SM S-3 to predict counterfactual values of cropland growth needed to satisfy observed growth in demand, assuming the there was not TFP growth in any region of the world. The results, translated into hectares by region (figure 1(A)), show that in the absence of TFP growth, instead of having observed a cropland contraction of ≈2 Mha between 2001 and 2010 in the sample countries, the amount of cropland expansion needed to satisfy observed demand would had been ≈127 Mha. The counterfactual also
reveals that, without TFP growth during this period, there would not have been any region with land contraction. Moreover, regions such as Developing Asia would have experienced rates of land expansion that surpass the combined land expansion observed in sub-Saharan Africa, Southeast Asia, and Latin America. In Latin America, where most of the cropland expansion during 2001–10 was observed (≈23 Mha), the regressions counterfactuals suggest an expansion of regional cropland of (≈49 Mha). Regarding GHG emissions, the imputed global emissions from observed net cropland conversion during 2001–2010 amount to a lower bound estimate of ≈1 gigaton of CO2 equivalent (Gt CO2eq) to an upper bound of ≈15 Gt CO2eq. In the counterfactual without TFP growth (figure 1(B)), such emissions would have increased to ≈17–84 Gt CO2eq. Finally, aggregating the regions into biomes, reveals that more than half (≈73 Mha) of the additional land needed to satisfy demand during 2001–10 would have come from the four most biodiverse ecoregions of the world (figure 4).

3.3. Recent rates of TFP growth seem insufficient to counteract expected short term increases in demand

While the counterfactual above suggests that the effects of TFP growth during 2001–2010 were associated with lower emissions and lower pressure on species-rich regions (relative to a counterfactual without TFP growth), it is natural to ask whether current trends in TFP growth are enough to counteract future changes in demand. We explore this by an additional counterfactual in which we use rates of population growth for 2020–2025 (UN 2017) and per capita GDP
growth projected for the period 2018–23 (IMF 2018) and substitute them in equation (1). We also use the rates of TFP growth most recently available: 2010–2015. Figures SM S-5, SM S-6 and S-7 indicate that population growth will slow down during 2020–2025 relative to 2001–10, while both domestic and revenue-share weighted foreign GDP per capita are projected to be higher than in 2001–2010. Meanwhile, figure SM S-8 indicates that for most of half of the considered sample, TFP growth rates during 2005–2015 were lower than during 2001–2010.

This counterfactual predicts land expansion in most regions of the world (figure 1(A)), for an aggregate central estimate of \( \approx 67 \text{ Mha} \); more than half of this expansion (\( \approx 35 \text{ Mha} \)) would occur in Latin America, followed by Southeast Asia (\( \approx 12 \text{ Mha} \)) and sub-Saharan Africa (\( \approx 11 \text{ Mha} \)). In other words, in contrast with the recent past, the growth in TFP in the sample countries seems insufficient to keep pace with demand, not only at an aggregated level, but also at regional levels. Around 60% (\( \approx 39 \text{ Mha} \)) of this growth in cropland is projected in the most biodiverse biomes of the world.

4. Discussion

Under the levels of international trade of 2001–2010, in most countries of the world, TFP growth is associated with expansion of croplands. Similar results using econometric analysis of observed data have been reported for Latin America (Ceddia et al. 2013). However, the indirect land use effects stemming from simultaneous TFP growth in many countries of the world more than offset the direct cropland expansion effects of domestic TFP growth as well as much of the pressure coming from increased income per capita, domestic and abroad. These results are consistent with the findings of Baldos and Hertel (2016), who found that TFP growth offset more than half of the pressure for cropland expansion to satisfy both income and population growth.

Our results also suggest that halting technological progress would actually entice more land expansions in some of the most biodiversity rich regions of the world resulting in greater GHG emissions. A caveat is that, in general, regression based counterfactuals need to be taken into account with caution. The assumption that no other regressors in the equation would have changed, is probably unrealistic. This is a feature of imposing a very restrictive partial equilibrium mechanism (only few variables change) on what is likely better characterized by more more complex equilibrium mechanisms in which, both demand and supply, would have been responsive to the prices that would have prevailed in the absence of technology. The inclusion of equilibrium feedbacks would likely result in lower estimates of cropland expansion due to adjustments in consumption or intensification (Hertel 2018).

Obtaining more estimates with more realistic assumptions is not without costs and would require using simulation models with their own set of assumptions and parameters, which sever the link between observed data and estimated effects. To the extent that we have privileged data-driven, empirical evidence, the discussed counterfactuals are probably better indicators of upper bound effects.

Pinpointing the extent to which counterfactual estimates of cropland expansion differ across models without equilibrium feedbacks (like in the current letter) and more complex models is a task worthy of future research (see Hertel 2018, for a conceptual roadmap). In the absence of such analysis, a non-rigorous and crude first approximation to these differences can be obtained by examining counterfactual estimates of land sparing in the existing literature. Two of these estimates measure the global land savings associated with TFP gains during the Green Revolution, over the period 1961–2010. Hertel et al (2014) use a global partial-equilibrium model focused on world agriculture (nicknamed SIMPLE) and find land savings due to pure TFP gains in global cereal agriculture in the order of 16 Mha. Not far from this value, using a computable general equilibrium model (GTAP-AEZ due to Hertel et al 2009), Stevenson et al (2013) estimate that TFP gains in cereals and legumes were associated with land savings in the order of 18 Mha 27 Mha. Both SIMPLE and GTAP-AEZ include feedback mechanisms through which both producers and consumers adjust their behavior to TFP-driven changes in prices.

In a related study, Burney et al (2010) estimate the land savings due to cereal yield growth using a model based on the physical relationships between changes in yields, cropland, and fertilizer use during 1961–2005. Similarly to the current letter, their approach does not include endogenous demand and supply responses to changes in prices. Their estimates indicate that in the absence of yield growth during 1961–2005, additional 1761 Mha hectares would have been required to satisfy the levels of demand observed in 2005. A lower estimate, which assumes satisfying the stagnant standards of living of a growing population, would have required 1111 Mha. These estimates are two orders of magnitude larger than those in Stevenson et al (2013) and Hertel et al (2014). Unfortunately, how much of these difference is due to the conflation of intensification and TFP growth in the yield growth measure used by Burney et al (2010), and how much is due to differences in the treatment (or lack thereof) of demand responses is unclear. In terms of size, and considering that we focus on the much shorter period of 2000–2010, our estimates are more in line with those in Burney et al (2010), reiterating the need to take them as upper bound effects.

Our predictions of the land needed to satisfy projected growth in income suggest that current rates of TFP growth seem insufficient to increase production
without using more land; this finding is similar to those reported by Steensland and Zeigler (2017). An important aspect to consider in the evaluation of future scenarios of cropland expansion is that TFP is the product of investments in research and development (RD) that may take from two to four decades to materialize (Fuglie 2017a). Recent estimates for the US suggest a lag of 19–23 years before initial investments translate into TFP (Baldos et al 2019). TFP growth also benefits from geographic spillovers; in some cases such spillovers can account for more than half of the TFP growth of some countries (Alston 2002, Gutierrez and Gutierrez 2003). TFP spillovers also occur from the RD activities carried out by international public research centers (Evenson 2003) and the private sector (Fuglie 2017a). Developed countries are more prone to benefit from both geographic and private RD spillovers than developing countries (Fuglie 2017a). In the latter, most of the investments are geared toward adapting technology to their local environments with limited evidence of geographic spillovers (Heisey and Fuglie 2018). In addition to RD, poor infrastructure and impediments to international trade significantly hinder the ability of developing countries to reach the same levels of productivity as those of developed countries (Tombe 2015).

Although TFP growth is key for increasing agricultural production without using more land and other resources, many knowledge gaps still exist. Measuring TFP growth is difficult. This study uses the TFP indices from the International Agricultural Productivity database produced by the US Department of Agriculture (Fuglie 2017b). These indices use input cost shares that are assumed to be invariant across regions and across time. Such invariance implies that the TFP indices will not reflect likely changes in the cost structure of the agricultural sectors, which may lead to biased measures of TFP growth (Alston and Pardey 2014). These measures also depend on the quality of the underlying data, which comes mainly from self-reported country statistics to FAOSTAT FAO (2018). Of particular concern is the measurement of physical capital (Alston and Pardey 2014). These measures are based on the inventories of on-farm machinery in FAOSTAT. Butzer et al (2012) argue that the composition of agricultural capital changes as countries experience structural change as part of the process of economic development, with machinery capital becoming less relevant as countries develop; therefore on-farm machinery is a poor proxy for changes in agricultural capital. Both the direction of the bias caused by measurement errors in cost shares and physical capital as well as whether these biases are systematic across countries are issues still unresolved in the literature (Fuglie 2012, Alston and Pardey 2014). From an econometric perspective, measurement errors are another potential source of biased parameters, to which the natural prescription is the use of instrumental variables. As discussed above, the IV estimators confirm the results obtained with the OLS estimates, which we prefer on precision grounds.

In addition to the measurement of TFP growth, we also have limited knowledge of the lag between the time investments are made and the time they result in TFP growth (Fuglie 2017a). The recent evidence is focused on the US (Baldos et al 2019). The structure of these lags is important for policy design and also for understanding how non-RD investments (e.g. infrastructure, and trade policy) affects them. Further exploration of the factors limiting technology spillovers across geographies is also crucial to understanding how to maximize the returns to RD investments. Recent evidence, for example, suggests transmission of knowledge from South America to sub-Saharan Africa as the latter advances its soybean frontier (Gasparri et al 2016).

The results of this letter suggest that, as countries get more integrates through international trade, the absence of technological progress to offset the demand of land from population and income growth, would result in increased cropland expansion across the world. Such levels of integration are likely to increase as trade policies are implemented in order to satisfy regional increases in demand for crops as a result of biofuel production and income growth (Baldos and Hertel 2016) and greater participation of developing countries in global value chains (Maertens et al 2012, Balié et al 2018). Ready access to international markets may be an important mechanism to alleviate the supply fluctuations of a more variable climate (Baldos and Hertel 2015). Projections suggest an increased reliance on imports, particularly in developing countries (OECD/FAO 2017) which will increase the connectivity of suppliers across the world. In this sense, the historical experience demonstrates that broad-based, global, technological progress has the potential of dramatically reducing global land demand. For places with both high agricultural and conservation value, where technology-led cropland expansion is a concern, land conservation is probably better achieved through better land use governance (Phalan and Green 2016).

5. Conclusions

In most countries of the world, the current levels of participation in international markets imply that regional TFP growth in agriculture is associated with land expansion. Yet, globally, the fact that many countries are exposed to TFP growth at the same time results in simultaneous increases in production, so that producers displace one another as they compete in destination markets. Empirically, such displacement takes the form of reductions in cropland associated with foreign TFP growth. These indirect land use effects more than offset the direct cropland expansion effects of regional TFP growth.
A counterfactual simulation of the land needed to satisfy the demand observed during 2001–2010 in the absence of TFP growth suggests the need to incorporate 125 Mha, half of which are in the three most biodiverse biomes of the world. Moreover, these counterfactual land needs would translate into a range from 17 to 84 Gt of CO2 equivalent, depending on the source of cropland, in contrast to the 1–15 Gt CO2eq imputed to observed cropland. In the presence of increasing globalization, these results suggest that broad based TFP growth may contribute to slow down global cropland expansion. Our projections of the land needed to satisfy projected growth in TFP per capita during 2018–2023 indicate that present time rates of TFP growth are insufficient to prevent further land expansion, reversing in most cases the trends in land contraction observed during 2001–2010.

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Data availability statement policy

The data that support the findings of this study are openly available at DOI:10.1093/ajae/aay088. Additional programs used in this study will be made available online with the article.

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