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Featured Article

The Effects of Agricultural Technological Progress on Deforestation: What Do We Really Know?

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Abstract *Increasing agricultural yields seem an obvious way to satisfy increasing demands for food and fuel while minimizing expansion of agriculture into forest areas; however, an influential literature worries that promoting agricultural innovation could enhance agriculture's profitability thereby encouraging deforestation. Clarifying the effects of agricultural technological progress on deforestation is therefore crucial for designing effective policy responses to the challenges faced by global agriculture. In this article we review the empirical evidence on these effects and synthesize estimates of future global cropland expansion. Our main insights are that: (i) the empirical evidence on a positive link between regional technological progress and deforestation is much weaker than what seems generally accepted; (ii) at a global level, most analysts expect broad based technological progress to be land saving; however, composition effects are important as low-yield, land-abundant regions are likely to experience further land expansion. Toward the future, empirical work understanding how localized technological progress in agriculture transmits through international trade and commodity markets will help to bridge the gap between the findings of local, econometric, studies on the one hand and global, model based, studies on the other.*

Key words: Deforestation, Technological change, Jevons paradox, Agricultural productivity.

JEL codes: Q16, Q23, Q55.

The competition for global agricultural land and forest resources is high on the development agenda as a result of climate change, increased commodity prices, and rising land prices. Land-cover change, experienced mostly through deforestation in the tropics, is the third-most important human-induced cause of carbon emissions globally, and the second-most important in developing countries (World Bank 2010). Tropical forests are also the largest repository of global biodiversity. Agricultural expansion (especially commercial agriculture) is the single most important cause of tropical deforestation (Gibbs et al. 2010).

Logically, technological change that improves productivity on existing agricultural land should save natural ecosystems (including forests) from being converted to agriculture. Indeed, many scholars have argued that agricultural research into increasing yields is critical to conserving the world's remaining forests and thereby limiting biodiversity losses (Green et al. 2005; Phalan et al. 2013) and greenhouse gas emissions (GHGEs; Burney, Davis, and Lobell 2010; Lobell, Baldos, and Hertel 2013). This argument is commonly known as the *Borlaug hypothesis* after Norman Borlaug (2007), who claimed that the intensification of cereal production between 1950 and 2000, partly as a result of Green Revolution technologies, had saved over one billion hectares of land from being brought into agricultural production.

However, the relationship between adopting yield-enhancing technologies and changes in land use is complex. Increases in productivity from new technologies increase the profitability of agriculture in comparison with alternative land uses (such as forests), thereby encouraging expansion of the agricultural land frontier (Angelsen et al. 2001). This outcome has been described as an example of Jevons' paradox (Rudel et al. 2009; Lambin and Meyfroidt 2011) due to its similarity to the situation described by that 19th century economist whereby an increase in the efficiency of coal use could lead to an aggregate increase in its use (Alcott 2005). The possibility of Jevons' paradox applying to agricultural land use has led many to be skeptical about the desirability of encouraging technological progress to reduce deforestation (Angelsen et al. 2001; Rudel et al. 2009; Gibbs 2012).

These seemingly contrasting views have a strong influence on academic debates that inform important policy issues about the role of agricultural technological progress in meeting global environmental goals. Two recent articles illustrate these contrasting perspectives in analyzing options for mitigating climate change; Burney, Davis, and Lobell (2010) simulate land use and agricultural GHGEs by assuming a counterfactual world that supplied the increases in food demand from 1961 to 2005 through expansions of cropland only (i.e., no yield increases). In these authors' simple model, demand does not respond to changes in crop prices, nor can producers adjust their inputs to changes in market conditions so that, consistent with Borlaug's view of the world, yield losses are assumed to be proportionally compensated though area expansion. Burney , Davis, and Lobell find that yield growth (of all crops covered by FAOSTAT) from 1961–2005 saved 1,514 million hectares (Mha; this is)more than twice the area of Brazil) from being converted to agriculture while avoiding net emissions of up to 161 Giga-tons of carbon (GtC).[1] Burney , Davis, and Lobell conclude that investment in agricultural research is a highly effective approach to mitigating climate change.

In the second example, Phelps et al. (2013) model the interactions between technological progress and performance-based payments for climate change mitigation in the Democratic Republic of Congo; these authors' fundamental premise is that technological progress encourages land expansion. In particular, Phelps et al. find that introducing improved varieties of maize and

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[1] *In an alternative scenario that keeps per capita demand fixed at 1961 levels, Burney, Davis, and Lobell (2010) estimate savings of 864 Mha and avoided emissions of 86.5 GtC.*

cassava as well as greater input usage lead to increased land profitability, which incentivizes forest encroachment and renders a payments-based conservation program unsustainable. However, a critical and in our view improbable assumption of their model is that farmers on the forest frontier face a perfectly elastic demand for their products.

These contrasting results are important since they have non-trivial implications on the way that resources are allocated to agricultural research for managing land-use changes and climate change. These results raise various questions, such as: Should agricultural R&D spending be scaled back in the tropics, especially for commodities that are largely produced for export or in situations of poor governance of natural resources? Can increased investment in agricultural research be a cost-effective approach to mitigating climate change? And lastly, if the benefits of research are spread globally through product and carbon markets, how should the costs of research investments be shared among countries? Thus, a first objective of this paper is to explore the strength of the empirical foundations underlying the fundamental assumptions of the Borlaug and Jevons' views of the world.

At the outset, we readily recognize that the relationship between agriculture and deforestation is complex and context-specific, and has been the subject of an already rich and growing body of literature. A broad review of this literature by Barbier (2001) bridges the transition from a "first wave" of cross-country studies to a "second wave" of region-specific case studies.[2] The interested reader is also referred to crucial work highlighting the roles of the following as drivers of land use change: infrastructure (Chomitz and Gray 1996; Nelson and Hellerstein 1997), property rights (Angelsen 1999; Liscow 2012), population growth (Cropper and Griffiths 1994; Foster and Rosenzweig 2003), the real exchange rate (Arcand, Guillaumont, and Jeanneney 2008), and supply chain configurations (Garrett, Lambin and Naylor 2013). Another useful starting point is the in-depth review of empirical findings on the drivers of deforestation presented by Angelsen and Kaimowitz (1999). One main conclusion in all of this literature is that while agricultural expansion is the main factor behind tropical deforestation, institutional and specific contexts strongly condition the outcomes.[3]

Against this backdrop, our main objective is to synthesize empirical work on the following question: Holding other things constant, what are the effects of technological progress on deforestation? Therefore, we focus on economic studies that measure the results of specific interventions to accelerate technological progress that can be reasonably treated as exogenous. This narrow focus is justified because much of the policy and academic debate on this issue lies in the uncertainty of whether investing the development of new agricultural technologies is an effective way of simultaneously

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[2] *Barbier's (2001) article introduces a special issue of* Land Economics *(Volume 77, Issue 2, 2001) focusing on the "Economics of Tropical Deforestation and Land Use", with articles examining various drivers of land use change such as price and market policies, infrastructure, governance, and property rights, among others.*

[3] *The important of specific contexts is difficult to overstate. For instance, Gutierrez-Velez et al. (2011) cite anecdotal evidence indicating that new investors in the high-yielding oil palm plantations of Ucayali, Peru, preferred to expand onto old-growth primary forests rather than previously cleared lands due to the uncertainty and disputed tenure over the latter. Similar conflicts exist in Indonesia and Malaysia (Teoh 2010). The book by Gibson, MacKean, and Ostrom (2000) is a valuable reference to the reader interested in understanding how local institutions shape the fate of forests, often in a more decisive way than policies emanating from a central government or planning agency.*

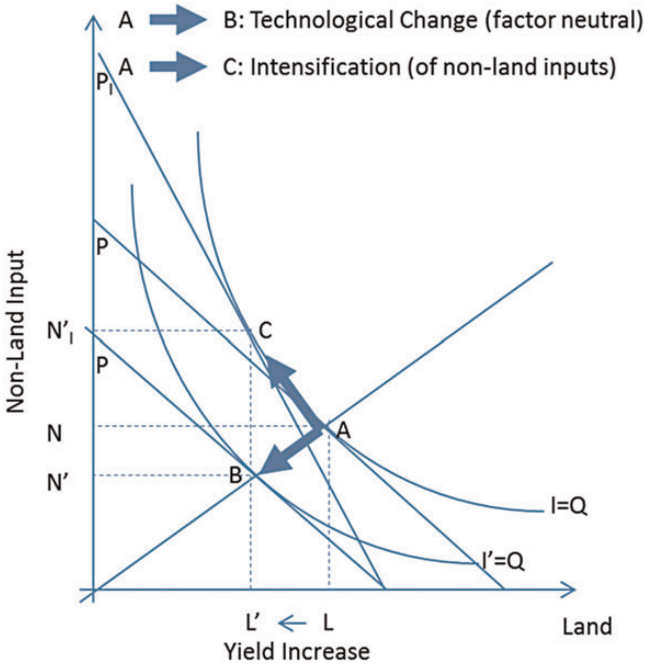
enhancing global food security and mitigating climate change. As exemplified above, the extreme bounds of such uncertainty (Borlaug vs. Jevons) are maintained assumptions in policy models that a priori condition their substantive findings. An additional objective of the review is to provide the most credible estimates of future cropland expansion in relation to assumed rates of technological progress—a much-discussed topic in recent literature (Lambin and Meyfroidt 2011; Deininger and Byerlee 2011).

An important outcome of this review is our finding that the econometric evidence on the relationship between technological progress and land use is generally weak. We can make some broad observations in general contexts, but the number of well-grounded empirical studies that support more context-specific conclusions is grossly inadequate for informing critical policy decisions. Therefore, our final objective is to highlight the state of the art with respect to methods and data used to analyze the relationship between technological progress and land use changes, whether they are at the local level or the global level; this leads us to identify important knowledge gaps to be addressed by future research.

While we recognize that multidisciplinary approaches are key requirements for better understanding the effects of technological progress on land use dynamics, we focus mainly on papers with an explicit economic treatment of the issues at hand. When we look to the literature from other disciplines, we do so through the lens of economics, as economic theory provides a consistent framework to reason through the complex relationship between technological progress and deforestation. Such a framework lends itself to formal tests of hypotheses, as well to a critical evaluation of existing findings, albeit given data limitations. Moreover, much of the skepticism on the land-saving effects of technological change (i.e., Jevons paradox) originates in the volume edited by Angelsen and Kaimowitz (2001b), which presents a review of the standard micro-economic theory relating technological progress to land use.

The rest of this article is organized as follows. In section 2 we review the conceptual underpinnings linking technological progress in agriculture to deforestation. Because several studies summarize this knowledge at varying levels of formality (Jayasuriya 2001; Angelsen et al. 2001; Angelsen and Kaimowitz 2001a), including a recent contribution by Hertel (2012), which focuses exclusively on formalizing the theoretical aspects of the Borlaug vs. Jevons debate, our treatment is brief. The main message of the theory is that the answer to the question “What are the effects of technological progress on deforestation?” is fundamentally empirical. Therefore, in section 3 we turn to a review of those available studies whose main objective is to econometrically isolate the effect of technological progress on deforestation. Interestingly, although much of the renewed interest on the effects of technological progress on deforestation is for mitigating GHGEs, an issue that is inherently global, all the available econometric work stops at the country border. Fortunately, there is a rapidly emerging body of literature reviewed in section 5 that uses simulation models to examine the effects of agricultural productivity growth on land use account for trade. Section 6 concludes by synthesizing lessons learned, identifying avenues for further research, and discussing some of the policy issues where we need a better understanding of the technological progress-deforestation nexus.

Figure 1 Sources of yield growth: intensification (or input/factor substitution) and technological progress (factor-neutral)



Notes: Technological change is represented by a shift of the isoquant. Intensification is represented by a movement along the isoquant.

The Economics of the Effects that Technological Progress in Agriculture Have on Land Use

Definitions

Much of the literature is framed in terms of intensification, which is defined as aggregate yield for all crops per unit of land (e.g., Rudel et al. 2009; Ewers et al. 2009; Phelps et al. 2013).[4] For the discussion that follows, we decompose yield growth into two components: technological progress and factor substitution. These components are shown in figure 1, where technological change is represented by a shift of the isoquant—a movement from point A to point B in figure 1—while factor substitution is represented by movement along the isoquant, that is, from point A to point C. Technological progress implies intensification in the sense that the same output can be produced with the same land area using fewer inputs. However, intensification can also occur independently of technological progress, as other factors substitute for land in response to changes in relative prices (e.g., more fertilizer leads to the same amount of output in less area as fertilizer becomes cheaper relative to land). Intensification can also occur through a change in product mix independently of technological change, as more productive crops substitute for less productive ones due to changes in relative product prices and market opportunities.

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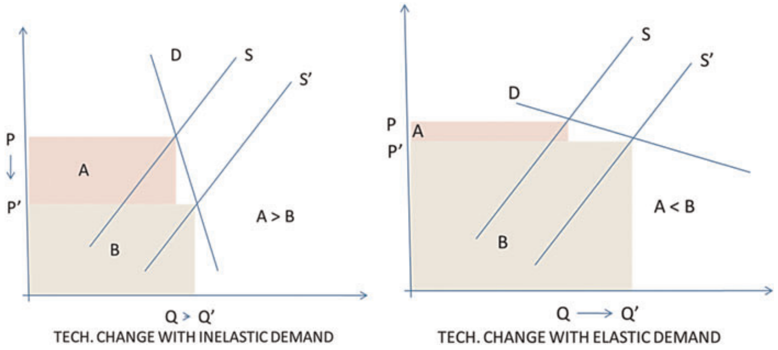
[4] *We focus on works with an explicit interest on the deforestation-technology link. Most mechanical technologies are not typically regarded as land saving and have little effect on yields (Binswanger 1978). Probably because of this, and with the exception of Maertens, Zeller, and Birner (2006), the issue of agricultural mechanization is not treated in the reviewed works, and we do not consider it in this paper.*

Figure 2 Technological progress and producers' revenues



Notes: In both panels supply shifts from S to S' as a consequence of technological progress. In both cases, output prices fall and quantities produced increase. However, only when demand is elastic (right panel) does producer's revenue increase (e.g, area denoted by B is larger than A), enticing a greater supply of farm-owned factors.

When Does Technological Change Promote Deforestation?

By definition, technological progress as shown in figure 1 lowers the minima of farmers' average costs curves, and therefore shifts the supply curve outward, leading to increased output and lower prices (unless demand is perfectly elastic, whereby prices would remain unchanged). As shown in figure 2, when product demand is elastic, producers' revenues increase due to the supply curve shift, incentivizing the supply of all farm-owned factors (Chavas and Helmberger 1996). In the case of factor-neutral technological progress this *may* entice land expansion (Angelsen et al. 2001).

In an article that formally examines the conceptual underpinnings of the Borlaug vs. Jevons debate, Hertel (2012) shows that the magnitude of such expansion is conditional on two forces that counteract each other: the potential for land expansion and the potential for factor substitution. In Hertel's (2011) framework, land expansion possibilities are captured by the *extensive margin* of production, formally given by $\eta^{ext} = \upsilon\theta_L^{-1}$, where υ is the land supply elasticity and θ_{L} is the share of land in total costs. The potential to increase yields in response to prices is captured by the *intensive margin*, given by $\eta^{int} = \sigma(\theta_L^{-1} - 1)$, where σ is the elasticity of substitution between land and non-land inputs. The implied supply elasticity in this model is given by $\varepsilon_S = \eta^{ext} + \eta^{int}$. Thus, no possibilities exist to substitute other factors for land, supply response is simply $\varepsilon_S = \eta^{ext}$, and any response to perceived change in prices will be realized through land expansion. At the other extreme, if the supply of land is fixed ($\upsilon \to 0$), there is no scope for land expansion, but farmers can still increase production if they can substitute away from land by using more non-land inputs. It should be noted that υ is partially policy-determined, depending on property rights and the governance of forestlands.

In Hertel's framework (2011; 2012), farmers are price-takers in non-land input markets, meaning that factor substitution is limited by the elasticity of substitution only. However, in forest frontiers, labor tends to be a scarce factor of production, and therefore changes in the demand for labor linked to innovations in agriculture affect wages, as does the relative valuation of labor within the farm-household. Because of this, Shively (2001) suggests that deforestation is better seen as a labor allocation problem. For example, if the subject of the study is a household where production and consumption decisions are made simultaneously, preferences about time allocation to work and leisure, as well as whether labor markets are complete, are important (Angelsen and Kaimowitz 2001a; Shively and Fisher 2004; Fisher, Shively, and Buccola 2005). If these decisions are separable, attention shifts to the effect of the innovation in the new equilibrium in the market for wage labor (e.g., Jayasuriya 2001).

Returning to the Borlaug vs. Jevons debate, Hertel (2012) suggests that these two seemingly polar views can be reconciled by recognizing that the elasticity of demand is proportional to the geographic scope of the innovation: Borlaug's hypothesis, which is global in nature, assumes fixed demand (that is, perfectly inelastic demand). Meanwhile, arguments about the potential land expansion effects that technological progress has on deforestation are made in the context of specific regions (Angelsen and Kaimowitz 2001b), where farmers are more likely to face a price-elastic demand. However, Hertel (2012) shows that even if there is an increase in deforestation in the innovating region in response to higher land productivity, the inelastic nature of global food markets is likely to induce "leakage" effects via trade, whereby increased production in the innovating region relieves pressures on forests elsewhere. Note that none of the above analytical frameworks capture the general equilibrium effects of increased agricultural productivity on incomes and food demand as an additional pathway in the relationship between technological progress and land use.

Implicit in this analysis is that innovations that occur at the forest frontier are likely to run a higher risk of leading to Jevons' paradox than are innovations that occur on cropland away from the frontier, or innovations that are broadly applicable across a wide range of production environments. Some of the studies reviewed in the next section reflect these biases in the scope of innovation.

A Note on the Appropriateness of Yield Growth as a Proxy for Measuring Intensification

As noted above, intensification can come from factor substitution as well as technological progress. Often, these occur simultaneously, as in the case of the Green Revolution, when introducing improved fertilizer-responsive varieties was accompanied by an increased use of fertilizer and other inputs (Pingali 2012). When interest is placed on the technological change-deforestation nexus, this simultaneity is a challenge for empirical analyses because it makes it difficult to separate the effects of factor substitution from the innovation per se. However, some prominent studies have used yield growth as a proxy for technological progress, thus confounding factor substitution and technological progress in the analysis.

An additional problem with using yields to analyze the effects of technological progress on deforestation is that in the long run, relative factor prices evolve in response to changes in factor scarcity. As documented by Hayami and Ruttan (1970), over the long run, changes in relative factor prices lead to factor biases in the development of new technologies. This process of *induced innovation* makes technological change, factor substitution, and land use change endogenous. Therefore, yield growth is a flawed proxy for the empirical analysis of causality between technological change and deforestation, and few studies are able to capture the endogeneity of technological change in relation to factor prices.

Finally, in the long run, income dynamics interact with deforestation. The literature on the Environmental Kuznets Curve focused on deforestation tries to disentangle whether income growth reduces deforestation as higher income consumers place more value on environmental and recreational services provided by forests and demand the conservation of remaining forests, thereby reducing the elasticity of supply of land to agricultural activities. (e.g., Bhattarai and Hammig 2001).

Local and Country Studies

We now review the empirical evidence on the fundamentally ambiguous relationships between technological progress and deforestation discussed in the previous sections, starting with studies at the national and subnational levels. We concentrate on studies whose main focus is to econometrically uncover the relationship between technological change and deforestation. All of these studies formulate an economic model that clarifies the specific channels through which technological progress influences deforestation. This allows the analysts to construct a reduced-form equation that estimates the effect of technological progress on forests. We start with studies that focus on innovations in forest-frontier regions, then we move onto studies that focus on technological progress in established lowland agriculture away from the forest frontier but accounting for linkages with upland regions on the frontier. Finally, we review the studies that are formulated at the national level. In all cases, we have purposely selected studies that have a clear empirical model that credibly tracks the relationship of interest between technological change and land use.

Technological Progress on the Forest Frontier

Three studies focus on technological progress on the forest frontier. Yanggen and Reardon (2001) evaluate the introduction of kudzu-improved fallows (a leguminous green manure crop) in the lowland Amazon basin surrounding Pucallpa, Peru, using a survey of farm households from 1998. The authors isolate the effects that technological change (area of kudzu-improved fallows in a household's land-holding) has on total deforestation (primary and secondary) by controlling a number of determinants of the choice of production technology, including household characteristics and proxies for input and output prices and markets. These authors find that adopting kudzu-improved fallows increase secondary forest clearing, but reduces the clearing of primary forests since kudzu compensates for the lower fertility of cleared secondary forests relative to primary forests. Although there is a net increase in total deforestation, the authors conclude that "the reduction of primary forest clearing is clearly a positive environmental impact, since these forests typically provide the greatest amount of environmental services."

Fisher and Shively (2007) use household survey data to analyze the effects that Malawi's Starter Pack Scheme (SPS), an agricultural assistance program that distributed small packs of free seed and fertilizer, has on agricultural expansion, as well as on forest product extraction for commercialization. The authors use multivariate regression to compare deforestation and forest product extraction outcomes between SPS receivers and non-receivers, and conclude that the SPS did not lead to increased deforestation.[5] Fisher and Shively also find that receivers of the SPS package had lower levels of extraction of commercial forest products; they suggest that receiving the SPS made farm labor relatively more valuable, thus discouraging forest-degrading activities.

Finally, Deininger and Minten (1999) use population and agriculture census data (for 1990 and 1991) combined with digital maps of land use and soils to investigate the effects of various socioeconomic and geographic factors on deforestation in southern Mexico. Their regression analysis is guided by a two-period model of labor allocation in which farmers can decide in the first period on expanding their holdings (by cutting down the forest) or investing in improving their productivity. The authors conclude that the "transfer of appropriate technology and generation of off-farm employment opportunities would be two ways to alleviate pressure on the natural resource base," (Deininger and Minten 1999).

Technological Progress away from the Forest Frontier Recognizing Lowland-Upland Linkages

Three studies formalize the archetypal Green Revolution story, where lowland irrigated rice-based systems in Asia located away from the forest frontier forged ahead with large-scale adoption of modern varieties and complementary inputs, while the upland agricultural sector near the frontier remained largely unchanged. In theoretical work, Jayasuriya (2001) shows that, with exogenous prices, lowland agricultural progress pulls production factors away from the uplands and hence the forest frontier, thereby reducing deforestation. However, the higher productivity of lowland agriculture increases national income and the associated demand growth may affect prices for upland agriculture products. If upland agriculture products are income-elastic (e.g., fruits and vegetables) then innovation in lowland agriculture could create incentives for upland deforestation.

Shively and Pagiola (2004) empirically explore the impact that irrigation development in lowland Palawan, Philippines, has on upland deforestation by linking upland and lowland regions through the labor market. Using panel data from a repeated survey of households in both upland and lowland communities, these authors find evidence of a boom in the labor market associated with higher cropping intensities following irrigation development in the lowlands. This has the effect, at least in the medium term, of alleviating land pressure on the forest frontier and reducing cropland expansion there. They also find evidence that the lowland development of irrigation "set in motion a virtuous cycle of poverty reduction and reduced forest pressure" Shively and Pagiola (2004). However, the authors do note the special geographical context of this study, in which the two agricultural regions are only one hour distant by foot.

The upland-lowland inter-linkage is also studied for rice in Indonesia by Maertens, Zeller, and Birner (2006) using a household model in which agricultural households trade off income and leisure, assuming that households in the region have no off-farm employment opportunities but are

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[5] *According to the authors, the two groups do not differ systematically on their observable characteristics, and therefore the use of the SPS can be regarded as randomly assigned.*

reasonably integrated into output markets. Maertens, Zeller, and Birner used recall data at the village level (assisted by secondary data sources and GIS) stretching back 20 years, on land-use changes in relation to changes in technology and population. These authors find that irrigation (yield-increasing) is associated with a reduction in deforestation while the use of tractors (labor-saving) encourages land expansion.

Technological Progress at the Country-level: India and Brazil

Foster and Rosenzweig (2003) combined village-level household surveys, censuses, and satellite data to study the effects of agricultural technological change, population growth, and rural industrial growth on forest dynamics in India from 1970–1999. These authors are guided by a general equilibrium framework that examines the allocation of land and labor among agriculture, industry and forestry that is applied to derive reduced-form equations estimated from panel data. Foster and Rosenzweig find that electrification and technological progress in agriculture led to increased wages and incomes and raised equilibrium rents for arable lands, thus leading to increased deforestation. Foster and Rosenzweig also note that a critical condition for this outcome was the relative tradability of agricultural products in India.

Garrett, Lambin, and Naylor (2013) analyze the effects of soybean yields on soybean expansion in Brazil, based on data from 1,180 counties in 2010. Using the ratio of soybean area to total potentially arable area (including forests, except those designated for permanent protection) as the measure of soybean expansion, the authors find a strong positive effect of yields on expansion, with an elasticity of 2.5 after accounting for transportation costs, biophysical conditions, institutions, supply chain characteristics, and the yield of competing commodities. Garrett, Lambin, and Naylor deal with the potential endogeneity between land conversion and yields by using an instrumental variables estimator whereby yields are instrumented by temperature, precipitation, slope, latitude, and longitude. These authors conclude that counties with higher total factor productivity advantages over other counties experience higher levels of land use conversion for soybean production due to increased land rents, which is consistent with an elastic demand for soybeans.

Cross-country Studies

Many studies have explored statistical relationships between agricultural productivity and land use by exploiting the variation observed across countries. Barbier and Burgess (2001) review the various approaches used to study the determinants of deforestation in cross-country regressions and indicate that in all of them, agricultural yield enters as a regressor and that the findings are generally mixed. This may in large part be due to data quality problems with common estimates of deforestation (Angelsen and Kaimowitz 1999). Barbier and Burgess (2001) in their analysis of a panel of tropical countries observed from 1961–1994, found that agricultural land expansion was significantly and negatively related to cereal yield, and positively related to GDP per capita, cropland share of total land, and agricultural export share of total exports. The elasticity for cereal yields was a surprisingly high −2.2, with the strongest effects seen in Latin America. However, when institutional and governance variables were included and the analysis repeated for a much smaller subset of countries for which such data were available, this yield effect disappeared. The disappearance of the land-sparing effects of yields on land expansion in cross-country settings when general indicators of governance are included is also reported by Ceddia et al. (2013), who use panel data methods to analyze the effects of yields (measured as the value of total agricultural output per ha of crop and pasture land) on agricultural expansion in six countries of tropical South America from 1970–2006.

Two influential papers examine the effects of yield growth on cropland expansion: Rudel et al. (2009) and Ewers (2009). A key question addressed in Rudel et al. (2009) is “Does the intensification of agriculture reduce cultivated areas and, in so doing, spare some lands by concentrating production on other lands?” These authors’ empirical strategy consists of calculating the percentage change in the ratio of yields to cultivated area for a range of crops between 1990 and 2005 using several geographic and sectoral cuts of national-level data from FAOSTAT. A positive percentage change in the ratio of yields to cultivated area is interpreted by the authors as strong evidence that yield growth did not cause land savings, while a negative sign is used as evidence to the contrary. The authors conclude that for the great majority of crops, yield growth did not lead to land sparing. Ewers (2009) examines the same question but regresses the change in per-capita total harvested area for all crops between 1979 and 1999 on the change in yields of all crops (measured in terms of kilocalories per hectare) during the same period for a sample of 123 countries. Ewers concludes that “land-sparing is a weak process that occurs under a limited set of circumstances, but that (. . .) can have positive outcomes for the conservation of wild nature.”

Using yield as an independent variable in cross-country studies carries several risks. Firstly, as already noted, yield growth is the final expression of both factor substitution and technological progress, and the reviewed studies confound these effects. More importantly, in a cross section of countries spanning several years, one or both of these effects could be simultaneously determined with land use change, and therefore the parameter estimates are likely to suffer from severe simultaneity bias. Further, these studies do not correct for many of the factors that changed over time, notably demand (although Ewers (2009) partially corrects for the effects of population growth by using per-capita area), and they make no attempt to introduce linkages through international trade.

Moreover, these cross-country studies are deeply flawed since they violate one tenet of causality analysis, that is, correlation is not causation. We include the studies here because they are widely cited to support maintained assumptions about the nature of the relationship between technological progress and land use. Indeed, Rudel et al. (2009) is the first instance we found that relates empirical findings on the relationship between yields and cropland to Jevons’ paradox.

Summary of Local and Country-level Studies

In summary, when looking at carefully executed econometric studies, a nuanced story emerges where technological progress at the local or country levels has generally reduced deforestation under different circumstances and settings. Does this mean that such a land-saving result is an empirical regularity? The cases of the lowland-upland settings of the Philippines

(Shively and Pagiola 2004) and Indonesia (Maertens, Zeller, and Birner 2006) seem to suggest that labor-biased technologies in the lowlands are likely to discourage forest clearing by attracting labor away from the forest margins. More surprisingly, the studies of innovation at the forest margin in Mexico (Deininger and Minten 1999) and Malawi (Fisher and Shively 2007), indicated land saving and reduced deforestation from technological progress, and even in Peru (Yanggen and Reardon 2001), where deforestation increased, innovation reduced the loss of primary forests. On the other hand, studies on the Green Revolution in India (Foster and Rosenzweig 2003) and soybeans in Brazil (Garrett, Lambin, and Naylor 2013) lend support to the notion that increases in productivity encourage land expansion.

The available evidence from cross-country studies is plagued by fundamental methodological issues and should be taken with extreme caution. Thus, the main lesson to draw is that polar cases in the spirit of the Borlaug vs. Jevons debate are a poor conceptual and empirical approximation to understanding the effects of technological progress on deforestation in the real world. Therefore, studies whose conclusions hinge on a priori assumptions about the technological progress-deforestation nexus (e.g., Phelps et al. 2013), should carefully consider the specific conditions of supply, demand, and labor markets to inform their modeling and parametric choices.

Technological Progress and Global Land Use Change

The studies reviewed above concentrated on the local effects of technological progress on the innovating region or country. As discussed in the theory section, technological progress in one region can influence production decisions elsewhere, as productivity-induced price changes are transmitted through product markets. Such readjustments in global production could relieve or encourage pressures in forests elsewhere. The studies reviewed in this section track the global land use change response to either localized or global technological progress by highlighting the interdependence of product and factor markets within and beyond country borders. In contrast to the previous section, these studies use economic models that either simulate the impact of past, large-scale episodes of technological progress in agriculture, or estimate the potential effects of alternative agricultural technological growth scenarios on future land use.

The relevant studies begin with Evenson and Rosegrant (2003), who employed the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) to analyze the effects of the Green Revolution using Evenson's (2003) estimated gains of total factor productivity (TFP) due to the adoption of improved varieties in the developing world from 1960–1998. This study was replicated by Stevenson et al. (2013), who employed the land use model of the Global Trade Analysis Project (GTAP), also known as GTAP-AEZ, and documented in Lee et al. (2009). We then discuss a handful of studies that seek to understand the effects of alternative *future* patterns of technological progress on reducing cropland expansion given projected trends in population and economic growth. The main motivation of these studies is to investigate the potential of increasing agricultural productivity as a way to mitigate GHGs emissions. These studies include Havlik et al. (2012) and Valin et al. (2013), who use the Global Biosphere Management Model (GLOBIOM); Rose, Golub, and Sohngen

(2013), who use a dynamic general equilibrium model augmented with heterogeneous land markets based on the dynamic GTAP model; Villoria et al. (2013), who use the static GTAP-AEZ model; Lobell, Baldos, and Hertel (2013), who use a "Simplified International Model of agricultural Prices, Land use and the Environment" (SIMPLE); and Schmitz et al. (2013), who use the "Model of Agricultural Production and its Impact on the Environment" (MAgPIE).

Categorizing the Models

Useful starting points for delving deeper into the diverse universe of modeling frameworks used to model global land use change are Michetti (2012) and Schmitz et al. (2013), both of which include copious references supporting the models. Where relevant, we draw from those reviews to describe the fundamentals of each modeling approach.

A first clustering of the models can be made according to whether they are partial equilibrium (MAgPIE, GLOBIOM, SIMPLE, and IMPACT) or general equilibrium (GTAP-AEZ and derivatives). However, the partial equilibrium models are quite heterogeneous. For instance, MAgPIE and GLOBIOM are dynamic recursive partial equilibrium models in which constrained optimization takes places at the grid cell-level and are therefore very rich in terms of spatial detail; these models are based on biophysical models that provide information on actual and potential productivity of natural land covers, as well as on cropland. (See Valin et al. (2013) and Schmitz et al. (2013) for details on the implementation of these bottom-up approaches to spatially explicit economic modeling).[6]

Partial equilibrium models assume both economic growth and agricultural productivity to be exogenous. This simplification allows a focus on the most relevant sectors under study and also provides more disaggregated representations of the agricultural, forestry, and bioenergy sectors. For instance, the current IMPACT model is very rich in representing water availability, as it partitions countries by watersheds (Rosegrant 2012). The GLOBIOM model uses information on yield, harvesting costs, and carbon stocks by examining 10x10 km grid-cells for 18 crops in 53 countries and regions in the world, whileMAgPIE also covers a large number of crops and can differentiate land at the grid-cell level. However, not all the partial equilibrium models are highly disaggregated, nor are they as complex. The SIMPLE model has the bare minimum essentials with only seven regions and an aggregated crop sector that competes with an aggregated non-crop sector. The strength of this minimalist approach is the ability to conduct extensive sensitivity analysis that helps to prioritize the needs for empirical estimation of model parameters.

The models based on the standard GTAP model (Hertel 1997) are general equilibrium models and, whether static (as in Stevenson et al. and Villoria et al.) or dynamic (Rose, Golub, and Sohngen), they provide an exhaustive accounting of factor and product market interactions that also allow agricultural productivity to influence land use through income and demand effects. The GTAP-based model differentiates staples such as rice, wheat

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[6] *The IMPACT model (Rosegrant 2012) is also a partial equilibrium model, but in contrast to the previous models, it is solved by a market equilibrium algorithm in which world prices change to equalize supply and demand such that world net trade is zero. Moreover, IMPACT's solution is independent of any biophysical model.*

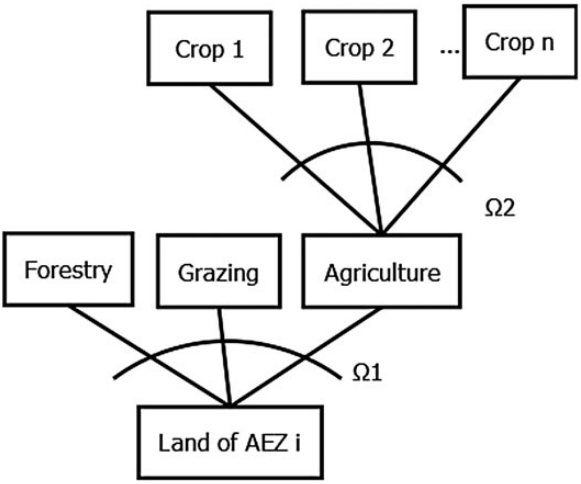
and coarse grains, as well as ruminant and non-ruminant livestock for 153 regions, thus allowing rich modeling of the agricultural and biofuel sectors. As explained below, the GTAP-AEZ-based models also use a consistent set of disaggregated land rents by agro-ecological zones (Monfreda, Ramankutty, and Hertel 2009; Lee et al. 2009), which allows land heterogeneity to be incorporated into general equilibrium analysis, albeit at a much coarser level of resolution relative to MAgPIE and GLOBIOM.

Modeling Land Allocation and Expansion into New Land

The simplest approach is to focus only on demand for cropland. For example, IMPACT models harvested area as a response to the crop's own price, the prices of other competing crops, the projected rate of exogenous (non-price) growth trends in harvested area, and water (Rosegrant 2012). However, only land allocations across crops within a fixed cropland endowment are considered and there is no mechanism for shifting land between cropland, pasture, and forests. The SIMPLE model is more stylized and considers only a "food" sector that is composed of a "crop" and a "livestock" good produced with aggregated cropland. As in IMPACT, there is no mechanism for shifting from cropland to pastures and/or forests. Because this is a model suited for analyzing the long run, SIMPLE assumes that over time some of the cropland is used for urban and infrastructure expansion (Baldos and Hertel 2012). In sharp contrast, MAgPIE and GLOBIOM consider a number of subclasses of land-cover types such as managed and unmanaged forests, as well as annual and plantation crops. Allocating land across different uses is governed by differences in the relative profitability accruing to each use.

The GTAP-based models use a constant elasticity of transformation (CET) function to model land cover changes in response to changes in returns to land. The GTAP-AEZ framework introduces land competition directly into land supply via a tiered, nested structure (e.g., Keeney and Hertel 2009), shown in figure 3. In the upper tier, crops compete with each other for land

Figure 3 Constant elasticity of transformation land supply nests in the GTAP-AEZ model



Notes: The terms labeled Ω are elasticities of substitution among (1) forestry, grazing and agriculture; and (2) among crops.

within a given Agro-Ecological Zone (AEZ). In the lower tier, crops as a whole compete with grazing and forestry for land within a given AEZ. In addition, different AEZs can be substituted in production of any single agricultural or forest product.

Calibrating the constant elasticity of transformation of land supply functions in the model is based on available econometric evidence, which is in short supply (Lubowski 2002; Barr et al. 2011). Evidence for the United States from Lubowski (2002), for example, indicates that the elasticity of land supply to forestry averages about 0.25 with respect to forest land rents. Barr et al. (2011) provide estimates of land elasticities for agriculture for the United States and Brazil, noting that this elasticity is low in the United States (<0.02), but much higher in Brazil (0.1–0.2), as might be expected given relative land endowments. Given the paucity of evidence on elasticities, most parameter values are gross extrapolations or estimates.

Regarding expansion into new lands, the static versions of the GTAP-AEZ model used by Stevenson et al. and Villoria et al. are similar to IMPACT and SIMPLE in that they do not allow "new land" (e.g., intact forests that are not currently exploited due to poor access) to be brought into production. However, Rose, Golub, and Sohngen use a dynamic version of the GTAP model and allow for endogenous cropland expansion into inaccessible forests using a land endowment elasticity parameter inferred from the Global Timber Model from Sohngen and Mendelsohn (2006). The GLOBIOM (Havlik et al. 2013) and MAgPIE (Schmitz et al. 2012) models include specific conversion costs for moving from non-agricultural (natural) land to cropland. Schmitz et al. for example, use a figure of $1,000/ha to convert tropical forestland into cropland. Land expansion in his model also depends on transport costs that are in turn determined by infrastructure.

Modeling Yields and the Productivity of Newly-converted Intact Lands

Yield modeling is fairly straightforward, since most models include an endogenous response based on substitution of non-land inputs for land, as well as an exogenous component to represent growth of total factor productivity (TFP). Obviously the elasticities of substitution between nonland and land inputs and the supply response of nonland inputs are critical parameters, although better empirical estimates are available than for the elasticities associated with changes in land cover type.

Another important aspect for modeling global land markets is assessing the productivity of lands that are currently under forests or other covers, and for which yield potential is unknown. The MAgPIE and GLOBIOM models are directly linked to biophysical models that provide the potential productivity of unused lands given its biophysical attributes. In the GTAP-based models, Stevenson et al. and Villoria et al. follow Hertel et al. (2010) and assume that new lands produce two-thirds of the yields of land currently in production. These authors analyze the sensitivity of their results to this assumption and find that although the estimated changes in crop land use are quite robust, there is great uncertainty around how much of this is converted from forests. Rose, Golub, and Sohngen, on the other hand, assume that the productivity of unmanaged land brought into production equals the productivity of the land endowment currently employed (aggregated over cropland, pasture and forests).

Model “Backcasts” with a Counterfactual

Evenson and Rosegrant and Stevenson et al. have attempted to backcast impacts of productivity on land use with an explicit counterfactual. These authors aim to provide estimates of the land-saving impacts of investment in the CGIAR through crop germplasm improvement (CGI) associated with the green revolution. The basis of these two papers are Evenson’s (2003) estimated contributions of the adoption of new varieties with improved germplasm to TFP growth of the main food staples in the developing world.

Based on Evenson’s TFP shocks, Evenson and Rosegrant constructed TFP shocks for investigating two scenarios. The first scenario assumed historically-observed TFP via CGI in the developed world, and thus aimed to isolate the combined effects of developing countries’ national and international research centers on the world food system. These estimates are deemed as conservative because they ignore the contribution of non-CGI elements to TFP growth. Due to uncertainty regarding the interactions between non-CGI and CGI contributions to TFP growth, Evenson and Rosegrant built lower and upper bounds of the combined effects of national and international research centers to TFP growth. These bounds offer a natural way to test the sensitivity of model results to the size of the actual TFP changes.

Using the IMPACT model, Evenson and Rosegrant found that crop area in 2000 was 2.8–4.6% less than would be the case for the counterfactual with no CGI in developing countries from 1965–2000. Land-saving estimates were higher for rice (7.5–9.4%)—one of the focus crops of the green revolution in Asia—than for other staple crops. A range of 3–4% of agricultural land saved between 1965 and 2000 corresponded to 9–12 million ha in developed countries and 15–20 million ha in developing countries, where the lower estimate assumes that all the TFP came only from CGI, while the higher estimate assumes that other non-CGI factors contributed to TFP growth.

The IMPACT model does not include a land market and cannot estimate the extent to which the additional hectares required under lower-yielding technologies in a counterfactual world would have come from forest, rather than from grazing land or other land cover with a lower value to society than forests. Stevenson et al. reanalyzed the Evenson-Rosegrant scenarios using the GTAP-AEZ (2009) and estimated a savings in cropland of between 17.9 and 26.8 million ha from CGI in developing countries from 1965–2000, somewhat less but in line with those of Evenson and Rosegrant. Since the GTAP-AEZ model incorporates land use conversion, Stevenson et al. were able to estimate that the additional cropland would come mainly from pastures (15.6 to 24.8 Mha) and some from forests (around 2 Mha).

Evenson and Rosegrant also recognized that in the absence of international research, governments would have more actively invested in improving agricultural productivity to prevent large price surges from harming their consumers. Accordingly, these authors devised a second set of shocks based on the assumption that in the absence of international centers, national centers would have been more active, thus compensating for some of the TFP growth that came out of the international centers. Under this scenario, the land use effects of the international centers are more moderate, as land use would have increased by only 1.5–2.7% (Evenson and Rosegrant 2003) or around 2% (Villoria 2011).

It is worth noting that although they focus on a restricted subset of yield changes (crop germplasm improvement in developing countries), these estimates of land saving are orders of magnitude lower than predicted by simple identities that do not account for feedback loops through prices of products, consumption demand, and land-use decisions but nonetheless have been widely cited (see Stevenson et al. 2013). Nevertheless, the lower net land-saving effects reported by these two analyses still represent a significant positive impact of agricultural research on land use, although the value of land savings are likely dwarfed by the welfare effects of agricultural research on food prices, and consequently on poverty and malnutrition (Stevenson et al. 2013; Evenson and Rosegrant 2003).

Model Forecasts that Relate Future Land Use to Crop Yields

Most of the studies in this section are motivated by the potential of using technological progress as a way of mitigating the climate change effects from GHGs associated with the expansion of agricultural and livestock activities. Havlik et al. uses GLOBIOM to build a counterfactual for from 2000–2030 in which (following FAO projections) world final calorie consumption of crops and animal products in 2030 are, respectively, 48% and 67% higher than in 2000. In their base run, these authors project forward historical rates of yield gain to estimate continued expansion of cropland of 108 M ha by 2030 as well as pasture at the expense of forest and other natural land. The sensitivity of these results to yields is demonstrated by scenarios demonstrating that if crop yields are held at 2000 levels, cropland increases by nearly 400 Mha, while a scenario with convergence of developing country yields to those of developed countries eliminates cropland area expansion by 2030. However, even with no aggregate increase in cropland, deforestation still occurs in some regions.

Valin et al. also employ GLOBIOM to study the implications of alternative development in agricultural productivity on mitigating climate change by reducing GHGs from land use change. These authors' empirical strategy consists of projecting land use changes for the year 2050, assuming that food demand is consistent with a "middle of the road" scenario of economic growth, and that agricultural yields keep increasing at observed historical rates. This scenario gives them a baseline loss of 499 Mha, of which 216 Mha come from forests and 283 Mha come from other natural covers. Against this baseline Valin et al. explore how much land would be saved if, instead of continuing current yield growth rates, developing countries converge to the levels of productivity of developed countries. In a scenario where technological progress closes 50% of current yield gaps and 25% of livestock feed efficiency gaps, the land conversion needed to feed their projected world decreases from 499 Mha to 278 Mha, of which 164 Mha would come from forests. Due to the large shares of land and crops used by livestock, Valin et al. demonstrate that focusing only on the crop sector misses an important part of the mitigation potential that stems from technological progress. For example, when these authors close 50% of crop yield gaps but maintain existing gaps in livestock feed efficiency use, the reduction of land needs relative to the baseline is only 54Mha.

Lobell, Baldos, and Hertel use SIMPLE to model impacts of investing to completely adapt to the effects of climate change on crop yields from 2006–2050. As in the two preceding studies, these authors also project future economic growth that is expected to shape food demand and estimate future cropland expansion using a set of standard projections representing non-extreme trajectories of population and income growth from United Nations organizations and the World Bank. In their reference scenario, crop yields increase by 60% but this still leads to an expansion of cropland by 23% (over 300 Mha), mostly in Latin America and Sub-Saharan Africa. With perfect adaptation to climate change, yields are 20% higher than the reference, but cropland expansion is 19% lower. The novel result is that investing in R&D for adaptation to climate change appears to be a cost effective approach to mitigating climate change through avoided forest conversion, and these results are robust with respect to a wide range of assumptions about key parameters. However, adaptation focused only on Latin America and Sub-Saharan Africa has very small global effects on cropland area, but increases expansion in Latin America and Sub-Saharan Africa—an illustration of the Jevons' paradox. The authors perform extensive sensitivity analysis that highlights the elasticity of land supply with respect to rents as a critically important parameter underlining the urgency of better empirical estimates.

Rose, Golub and Sohngen employ a dynamic recursive general equilibrium model based on the GTAP-AEZ framework that allows for endogenous increases of the total land endowment into inaccessible forests. These authors ask the question: Do relative patterns of productivity matter? Their main finding is that if the relative TFP growth of Latin America and Sub-Saharan Africa is higher than overall global average TFP growth, these regions will experience deforestation above baseline projections. These results lend further support to the so-called Jevon's paradox, that is, productivity growth focused on the frontier (i.e., Latin America and Sub-Saharan Africa) leads to deforestation in those regions. These results also seem to be in line with Valin et al. who find increased emissions in tropical regions due to technological progress as regions converge in technological level, in spite of global land savings.

Although the main focus of Schmitz et al. (2012) is the interaction between trade liberalization and forest conservation policies on land use changes, one of their scenarios examines investments in Latin America, Sub-Saharan Africa, and Pacific Asia to accelerate yield growth by one percentage point a year. This was found to be effective at saving forests (22.4 Mha less deforestation, with most of this in Southeast Asia), although far from offset deforestation in those regions of 229 Mha in their base run Schmitz et al. is one of the few studies that has explicitly modeled forest protection policies, and they conclude that such policies must be a large part of the solution to tropical deforestation, although accelerating crop productivity through investment in R&D can help.

Finally, Villoria et al. provide an estimate of the global impacts of a location specific technological change on the forest margin. These authors selected oil palm in Indonesia and Malaysia because of its important role in tropical deforestation and greenhouse gas emissions globally, and a call for improving yields as a remedy to forest encroachment. Indonesia and Malaysia are the world's dominant palm oil exporters, although they export into larger vegetable oil markets with high substitution among different oils. Villoria et al. then explored whether the incentive to expand oil palm areas by adopting higher-yielding technology would be outweighed by price effects in global markets from increased palm oil supply—that is, the

Jevons vs. Borlaug issue. Assuming that technology could be used to close one-third of the yield gap over 25 years, or a 59% increase in yields, Villoria et al. found a small acceleration of forest conversion to cropland of 0.13 Mha in Indonesia/Malaysia, but a global saving in land of 0.3 Mha and a net reduction in GHG emission through increased forestland in other countries such as India, Canada, and Brazil. These findings are noteworthy in that they show that even for a specific, locally-targeted intervention, local impacts can be outweighed by global impacts through international trade. In contrast, for small players in international markets, the impacts of technological progress can be partially absorbed by deforestation in the innovating region (Mosnier et al. 2014).

Summary Results and Limitations of the Models

Given the variability in data, assumptions and results, three main qualitative insights seem to be robust from the review above: (*a*) using baseline projections based on largely accepted figures regarding population and income growth, future land expansion is unavoidable; (*b*) accelerating technological progress that results in worldwide agricultural TFP growth reduces the amount of deforestation relative to the baseline; and (*c*) composition effects matter, as even when global TFP growth saves land globally, the tropical regions of Latin America and Sub-Saharan Africa are likely to experience increased deforestation as technology improves in those regions. In other words, these carefully crafted modeling endeavors seem to suggest that the Borlaug and Jevons views of the world are not mutually exclusive, but rather coexist as a result of market-mediated adjustments in worldwide supply patterns in the wake of global or local technological progress

Another relevant issue is the heavy focus on GHGEs being considered the only environmental cost of deforestation. In all cases, GHGEs are modeled through coefficients of emissions from different land cover types—cropland, pasture, and forest—disaggregated by major ecologies such as the humid tropics, dry tropics, temperate and boreal forests. This disaggregation, together with assumptions about the price of carbon, allows land use changes to be valued, at least with respect to carbon emissions. However, carbon sequestration is only one environmental service provided by forests, so these studies tend to undervalue forests relative to other land uses.

Further, the models are limited in their ability to represent what are likely to be unpredictable endogenous institutional responses to steep price increases or large amounts of deforestation. This is especially the case for endogenizing policy and institutional changes that are critical to long-run analyses of up to 50 years, which are commonly employed in the reviewed studies. Because of this, it is important to understand that expanding cropland of the order of 300+ ha in Lobell, Baldos, and Hertel, Valin et al., and Havlik et al., in some cases at the expense of forests, but also out of other natural covers, are projections that abstract from policy responses to protect forests. A challenge to current modeling frameworks is how to endogenize policy that reflect the changes in forest valuation as countries climb the income ladder. Although there is much uncertainty about the turning point hypothesized in the Kuznet curve for societies' valuation of environmental services provided by forests, there is little doubt that middle income countries such as Brazil are already exhibiting high societal values and a willingness to protect their forest resources (Nepstad et al. 2006). It would be interesting to incorporate these changes in behavior as a function of income in the frameworks revised above.

Finally, this review has shown that our theoretical understanding of the productivity-land-use relationship is somewhat ahead of our abilities to make empirical estimates. The results of model comparison exercises (Nelson et al. 2013), as well as studies of the robustness of results given parametric choices (Lobell, Baldos, and Hertel 2013) call for more refinements on the supply side of the model, as well as validation of model results against observed data.

A Note on the Treatment of Land Institutions in the Revised Studies

Throughout the paper we have emphasized that institutional aspects regarding property rights and the enforcement of forest protection laws are likely to be more important determinants of deforestation than technological progress per se. This raises the question: How have the econometric and simulation models discussed above dealt with this issues? In most of the country-level studies, land tenure regimes are controlled for either directly or indirectly by using dummy variables and other indicators such as ownership status. For instance, Fisher and Shively use village fixed effects to control for difference in forest management institutions associated with the effectiveness of village heads in regulating access to communal lands. Further, Deininger and Minten include shares of communal agricultural land and indigenous people in each observed *municipio* to control for institutional aspects related to land tenure. In the study by Yanggen and Reardon, forest resources are owned by farmers. Deininger and Minten and Garrett, Lambin and Naylor present results of in-depth discussions on the interactions between land institutions and technological progress in the contexts of Mexico and Brazil, respectively.

In the cross-country studies of Barbier and Burgess and Ceddia et al., property rights and the enforcement of forest protection laws are controlled by adding an index of governance, based on variables such as corruption, democracy, and political stability. However, using general governance indicators rather than indicators specific to natural resources and the lack of time series information on the governance variables raises major questions about the findings on governance. Many of the simulation models include the implicit assumption that property rights are well assigned. For example, the family of GTAP models includes a representative household that owns endowments of land, labor, and capital and sells them to representative firms in exchange for wages or rents.

Future Directions

The role of technological progress in agriculture has received increasing attention because of the constraints faced by the global food system. The main concerns here are that yield progress has been slowing at the same time that we appear to be running out of land. Many have indicated that investment in agricultural research that increases yields is a way to produce more food while saving land from further encroachment into forest areas. Recent studies have also indicated that investment in agricultural research by saving land may be a cost-effective way to mitigate climate change (Lobell, Baldos, and Hertel 2013). However, an influential body of theoretical and empirical work has promoted the idea that technological progress may lead to increased deforestation. Thus, our first objective was to examine how strong the empirical foundations of these contradicting views of the world really are.

Surprisingly, there is an extremely limited number of studies that try to isolate the effects of technological progress in agriculture on deforestation. Nearly all of these studies find that when technological progress is biased towards increasing land productivity, cropland is saved, thereby reducing deforestation (Yanggen and Reardon 2001; Maertens, Zeller, and Birner 2006; Fisher and Shively 2007). One of the most widely cited studies used to justify the failure of technological progress on reducing deforestation, that of Rudel et al. (2009), is merely a correlation analysis without causal evidence. Therefore, the first lesson of this review is that the empirical support of Jevons' paradox (i.e., technological progress leads to more deforestation) is much weaker than what seems to be accepted in the literature (Angelsen and Kaimowitz 2001c; Hertel 2012; Phelps et al. 2013). In terms of future research, while more careful studies examining this relationship in different contexts will be welcomed, the bottom line is that analysts should carefully design their models to fit the situation at hand, and not simply take the polar views represented in the Borlaug vs. Jevons debate as their starting assumptions.

We also found a large gap between the literature at the national and subnational levels, and the literature concerned with the long-run sustainability of the world food system. The bridge between the local and global land-saving effects of technological progress is given by the notion of "forest leakage", which captures the idea that through international trade, production increases in one region of the world can offset pressures in other regions, thus leading to global land-saving even if deforestation exists in the innovating region (Hertel 2012; Meyfroidt et al. 2013). These potential forest leakage effects may be important in the decision to invest in agricultural research as a means of mitigating GHG emissions through reduced forest conversion. Greenhouse gas emission is a global issue and a fair assessment of the benefits of investment should therefore be global, not local. Therefore, investigating the forest leakage or indirect land-use effects of technological progress is an area where fruitful research can shed light on whether the global land-saving effects of technological progress overcome potential increases in deforestation in the innovating regions. (See Villoria and Hertel 2011, for a discussion of the importance of bilateral trade patterns on global land use). Knowledge of such leakages also has important implications for sharing R&D investment costs between local and global actors.

We conclude that research on the nexus of technological change and land use offers a fruitful area for future research; it not only links country level and global economic analyses, but also integrates disciplinary perspectives, and improves models. Models such as GTAP, which are built for short- to medium-term projections, are being stretched to 50 years with implications for choice of critical elasticity parameters. In the long term, there is scope to further endogenize variables regarded as exogenous in these models, for example investment in R&D and land supply response. Given the importance of the extensive and intensive margin in determining land use changes, careful econometric estimation of land supply and yield elasticities to food prices could greatly increase the accuracy of land use projections. Efforts to estimate these parameters in different contexts, including countries with large forests reserves, are particularly needed.

Another issue that deserves further refinement is the incorporation of new, unexploited lands into the models. Currently, most approaches limit land endowments to commercial forests (Hertel, Rose, and Tol 2009). The main difficulty in doing this is to impute rents on forestlands that are in their natural or pristine states. One avenue is to exploit the growing availability of datasets on land cover and land use (Monfreda, Ramankutty, and Foley 2008; Ramankutty et al. 2002), as well as on biophysical variables to estimate land rents based on the potential productivity of land. Unfortunately, many of the data required to do this are dated (Ramankutty et al. (2002) has the most comprehensive geo-referenced, gridded, global yield data for 175 crops, circa 2000), and a concerted global effort is needed to provide regular updates (Hertel, Britz, et al. 2010). A comprehensive database should also include pastures given the strong links between crops and livestock in land use changes. Additional efforts to understand the productivity potential of hitherto unexploited lands are fundamental for accurate modeling of land needs and policy evaluation.

In closing, we note that the questions "What are the effects of technological progress on deforestation?" and "Can technological progress stop deforestation?" are often confused. In this review, we examined only the first question. But if focus is on the latter, it should be recognized that the impact of technological change on land savings is only one among many factors that drive land-use change and deforestation. For many rapidly expanding commodities on the forest margin, such as pastures, soybeans and oil palm, the effects of higher commodity prices and investments in infrastructure, combined with poor governance of land and forest resources are likely to dwarf the effects of technological change. In other words, expansion at the intensive margin through new technologies is unlikely to succeed if it is cheaper to expand at the extensive margin where forestland is readily available and poorly governed. Recent experience with better governance and monitoring of the Brazilian Amazon has shown a dramatic drop in rates of deforestation, even as commodity prices have risen sharply in the past five years.

We should also note that we have focused on only the technological component of intensification. A stronger case may be made that intensification through changing product mix induced by new market opportunities has produced significant deforestation. The recent oil palm expansion at the expense of forests in Southeast Asia (Koh and Wilcove 2008) and an earlier surge in banana exports in previously forested areas of coastal tropical Latin America (Wunder 2001) are examples of such types of intensification, but they did not result from technological progress. In fact, Wunder argues that later technological progress in bananas in Ecuador arrested forest encroachment.

Finally, the available evidence reviewed in this paper suggests that given likely rates of technological progress and future growth in demand for food, the world is still far from "peak cropland" (Ausubel, Wernick, and Waggoner 2013). In one of the most carefully constructed sets of scenarios, Lobell, Baldos, and Hertel suggest that by 2030, another 300 Mha or about 20% of today's cropland will be brought into production, undoubtedly at significant environmental costs. Efforts to scale up investments in technological progress and regulate land expansion into less environmentally sensitive areas can reduce these costs, but as we have consistently argued in this paper, they must be designed globally by account for "forest leakage" effects.

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