

Agricultural technology, global land use and deforestation: A review

James Stevenson¹, Derek Byerlee², Nelson Villoria³, Tim Kelley⁴, Mywish Maredia⁵

Version: 1st June 2011

Abstract

We review the complex relationship between the adoption of new agricultural technologies and land use change, explaining the multiple causal pathways of impact between adoption of yield-increasing technologies (such as an improved variety), land use change in general, and deforestation in particular. We present new estimates of the impact of crop germplasm improvement in the major mandate crops of the CGIAR between 1965 and 2004 on global land-use change, using the Global Trade Analysis Project Agro-ecological Zone model (GTAP-AEZ): a multi-commodity, multi-regional computable general equilibrium model linked to a global spatially-explicit database on land use. We find support for Norman Borlaug's hypothesis that increases in cereal yields as a result of widespread adoption of Green Revolution technology have saved natural ecosystems from being converted to agriculture, although our results suggest that this effect is of a much smaller magnitude than Borlaug argued. We find that the total agricultural area in 2004 would have been between 17.9 and 26.7 million hectares larger in a counterfactual world which had not benefited from crop germplasm improvement since 1965. Of these counterfactual hectares, 12.0 to 17.7 million hectares would have been in developing countries. This estimate is similar to that of the paper by Evenson and Rosegrant from 2003 (24 to 32 million ha globally) using the IMPACT model. The results of additional simulations in GTAP on productivity shocks to soybean in Brazil and oil palm in Indonesia and Malaysia are also reported to illustrate the similarities and differences between productivity improvement in cereals and oilseeds. We conclude by suggesting how the CGIAR can best ensure it maximizes its potential positive impact on the issue of global land-use change.

1: CGIAR Independent Science and Partnership Council Secretariat, United Nations Food and Agriculture Organisation, Rome. Email: james.stevenson@fao.org

2: Chair, CGIAR Standing Panel on Impact Assessment

3: Department of Agricultural Economics, Purdue University

4: CGIAR Independent Science and Partnership Council Secretariat, United Nations Food and Agriculture Organisation, Rome

5: Member, CGIAR Standing Panel on Impact Assessment and Department of Agricultural, Food and Resource Economics, Michigan State University

1. Introduction

The competition for global agricultural land and forest resources is centre stage on the development agenda as a result of climate change, rising commodity prices, and rising land prices. Land-cover change is the third most important human-induced cause of carbon emissions globally and the second most important in developing countries (World Bank, 2010). In turn, agricultural expansion, especially commercial agriculture is the single most important determinant of tropical deforestation. Between 1980 and 2000, 83% of all new agricultural land in the tropics came from either intact forests (55%) or disturbed forests (28%) (Gibbs et al., 2010).

Many have argued that agricultural research to increase yields is critical to saving the world's remaining forests and in doing so, limiting losses of biodiversity (Green et al, 2005) and greenhouse gas emissions (Burney et al, 2010). Technological change that improves productivity on existing agricultural land saves natural ecosystems (including forests) from being converted to agriculture. This is commonly known as the *Borlaug hypothesis* after Norman Borlaug (2007), who claimed that the intensification of agriculture between 1950 and 2000, partly as a result of the technological change made possible by the Green Revolution, had saved 1.2 billion hectares of forest.

However, the relationship between adoption of new technologies and land use is complex. Increases in productivity from new technologies also increase the profitability of agriculture in comparison with alternative land uses (such as forest) thereby encouraging expansion of the agricultural land frontier. Several case studies in Angelsen and Kaimowitz (2001) support these types of land use effects resulting from technological change.

It is not possible to sort out these relationships directly in empirical studies, since the counterfactual cannot be observed. Moreover, the pathways through which technological change has impacts on land-use change are manifested through markets for agricultural outputs and the factors of production. For these reasons, the impacts of technical change can only be estimated econometrically or estimated through models.

The CGIAR is a major source of technologies for food crops, and its impacts on productivity have been well documented (Renkow and Byerlee, 2010). However, impacts of the CGIAR system on the environment have received little attention (Renkow, 2010). The land use effects of technological change may represent the single most important source of environmental impacts of the work of the CGIAR globally. Earlier studies have argued that CGIAR-led agricultural technologies have significantly *reduced* agricultural expansion (over what otherwise would have emerged), and in doing so potentially saved forests (Nelson and Maredia, 2001; Evenson and Rosegrant, 2003).

This paper takes a two-pronged approach to address these questions with respect to the CGIAR. In section 2 we open the discussion and examine the theoretical basis of the relationship between increased agricultural productivity and changes in land-use globally and for developing countries, briefly reviewing earlier modelling and estimation efforts. Section 3 provides estimates of land saving effects of technological change based on a computable general equilibrium model. Then, in section 4, we start from an analysis of what is happening on the land-forest frontier as documented in global statistics and research studies from the last 10 years, and ask to what extent new technologies or institutional and policy contexts, especially governance of land and forest resources are contributing to deforestation.

The combination of these two approaches enables us to provide an informed view of the relationship between CGIAR research and land-use change. We conclude, in section 5, by suggesting how the CGIAR can most effectively contribute in future to the twin goals of maximising agricultural productivity and minimising forest loss.

2. Opposing perspectives on agricultural intensification and land use change

2.1 Land saving effects: The Borlaug hypothesis

Norman Borlaug’s response to environmental critiques of the Green Revolution is summarised in the following quote:

“If the global cereal yields of 1950 still prevailed in 2000, we would have needed nearly 1.2 billion more hectares of the same quality, instead of the 660 million hectares used, to achieve 2000’s global harvest. Moreover, had environmentally fragile land been brought into agricultural production, the soil erosion, loss of forests and grasslands, reduction in biodiversity, and extinction of wildlife species would have been disastrous.” Borlaug (2007)

Borlaug argues two related points here. The first argument is that increases in agricultural yields have saved new agricultural lands from being brought into production. The second is that the “saved land” provides valuable ecosystem services by maintaining natural areas. In this paper, we primarily address the first of these hypotheses (how much land has been saved by new technologies for food crops), although section four of the paper does touch on the value of the ecosystems services and related tradeoffs.

2.1.1 Estimates based on the global food and land equation

A simple identity links global population (N), food consumption and production (q), land area (L), and agricultural yield (q/L): with demand on the left hand side, and supply on the right hand side (Angelsen, 2010):

$$Nq/N \equiv q/L * L \quad (1)$$

Borlaug’s estimates noted above involve simple calculations using this identity – if yields do not change but population increases, then more land is required to feed everyone even at the same level, not to mention rising per capita consumption across the board. The variables for this identity for cereals, which includes the world’s major food staples for the period 1961 – 2008² are given in Table 1. During this period, global population more than doubled and per capita consumption also increased by 20%. The increase in cereal production to meet this increase in demand has overwhelmingly come from an increase in yields. Area harvested increased by only 7%.

Table 1: Variables of the global food and land equation between 1961 and 2008

	1961-1963	2006-2008	% increase
Demand side			
Population (billions)	3.13	6.62	111.6
Cereal consumption per capita (kg/capita/year—food, feed, and other uses)	294.3	358.3	21.8
Supply side			
Area harvested (M ha of cereals)	653.7	697.2	6.7
Cereals yield (t/ha)	1.41	3.40	141.5

The argument that in the absence of the observed 140% increase in cereal yields between the 1960s and 2000s, the area under cereals would have expanded by a similar percentage is based on a number of assumptions. First, population growth and economic growth are assumed exogenous to agricultural

² This is the longest range for which the data are available through <http://data.un.org/>

productivity³. Theory (and some evidence) might suggest that higher agricultural productivity may reduce both human birth rates and death rates, leading to ambiguity. The causal contribution of agricultural productivity growth to economic growth at early stages of a country's development is widely recognized (Christiaensen et al, 2010; Valdes and Foster, 2010), even if it is difficult to establish empirically (Gollin, 2010).

More importantly the estimates of land savings based on the above identity do not consider effects on prices. In the absence of yield increases, prices would have increased and curtailed at least a proportion of the per capita consumption increases observed in developing countries with of course, negative implications for the number of people suffering from hunger or malnutrition. In addition, on the supply side, higher output prices would induce a supply response by farmers. Keeney and Hertel (2009) note that this is an important area of uncertainty in the models that attempt to estimate the impact of biofuels on land-use. Farmers may boost supply by increasing cropping intensity or using more capital (e.g., irrigation) and labour (e.g., weeding). Given that yields and consumption are endogenous to the agricultural system, simple calculations such as those performed by Borlaug and many others since, tend to overestimate the extent of land savings relative to a more realistic counterfactual.

Nelson and Maredia (2001) attempt an approximation to a counterfactual by applying a coefficient of substitution between yield and area of 1:0.5 on the supply side based on Evenson (unpublished estimates). According to this calculation, over the 30 years from 1960s to 1990s, area in seven CGIAR-mandated crops (wheat, rice, maize, pulses, barley, cassava, and sorghum) increased by 75 million ha at the time that yields approximately doubled. Application of the above coefficient suggests that **land in production would have been 230 million ha higher than observed, compared to 1.2 billion estimated by Borlaug**. If only yield increases from crop germplasm improvement (CGI) are considered, along with the effects on changes in cropping intensity, global estimates for land savings would be around 110 million ha (Maredia 2003, unpublished report). However, their study does not account for the impacts through food prices on consumption and production, or impacts through factor markets.

2.1.2 Estimates based on global partial equilibrium modeling

Better economic modeling approaches are needed to account for various market effects of technical change. For the CGIAR, Evenson and Rosegrant (2003) conducted a comprehensive modeling analysis based on the findings of a major initiative that estimated the adoption and impact of CGI in developing countries (Evenson and Gollin, 2003). They compared the observed level of technology in developing country agriculture in 2000 (referred to as the "base case") to a counterfactual case of no CGI since 1965. In this counterfactual scenario, developed countries still benefited from the CGI consistent with their historical record for the period.

Evenson and Rosegrant used the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), a multi-market, multi-country model with 17 crop commodities⁴ (very close to those covered by Nelson and Maredia) and 35 countries or regions. In IMPACT⁵, crop supply and demand factors determine the market-clearing prices, quantities supplied and consumed, and the trade volumes.

³ More sophisticated approaches to modelling these impacts (using partial equilibrium or computable general equilibrium (CGE) models) make similar to assumptions about population, although it is possible to make population endogenous if a dynamic CGE approach is used. With regards assumptions about the links to economic growth, the key advantage of CGEs is the ability to make the impact on the rest of the economy endogenous.

⁴ The number of commodities and country groups featured in IMPACT has changed over time. The 2002 version (Rosegrant, Meijer and Cline, 2002) features 36 countries and 16 commodities: Beef, Pork, Poultry, Sheep and goat, Eggs, Milk, Maize, Other coarse grains (barley, millet, oats, rye, sorghum), Rice, Wheat, Cassava (and other tubers), Potatoes, Sweet potatoes and yams, Meals (e.g. copra cake, groundnut cake), Oils (vegetable oils and products, animal fats and products), Soybeans. Evenson and Rosegrant (2003) report that the version they used contained 17 commodities across 35 countries.

⁵ The equations here are for IMPACT 2005 version. Subsequently, additions were made to the model to incorporate supply and demand schedules for water (Rosegrant et al, 2008).

In IMPACT, domestic crop production is determined by area and yield response functions. Harvested area is specified as a response to the crop's own price, the prices of other competing crops, the projected rate of exogenous (nonprice) growth trends in harvested area, and water (eq. 2). The projected exogenous trend in harvested area captures changes in area resulting from factors other than direct crop price effects, such as expansion through population pressure and contraction from soil degradation or conversion of land to non-agricultural uses. Yield is a function of the commodity price, the prices of labour and capital, water, and a projected non-price exogenous trend factor. The trend factor reflects productivity growth driven by technology improvements, including the research outputs of the CGIAR (eq. 3). Annual production of commodity i in country n is then estimated as the product of its area and yield (eq. 4).

$$\text{Area response: } AC_{mi} = \alpha_{mi} \times (PS_{mi})^{\varepsilon_{im}} \times \prod_{j \neq i} (PS_{mj})^{\varepsilon_{jn}} \times (1 + gA_{mi}) \quad (2)$$

$$\text{Yield response: } YC_{mi} = \beta_{mi} \times (PS_{mi})^{\gamma_{im}} \times \prod_k (PF_{mk})^{\gamma_{ik}} \times (1 + gCY_{mi}) \quad (3)$$

$$\text{Production: } QS_{mi} = AC_{mi} \times YC_{mi} \quad (4)$$

where AC = crop area; YC = crop yield; QS = quantity produced; PS = effective producer price; PF = price of factor or input k (for example labour and capital); Π = product operator; i, j = commodity indices specific for crops; k = inputs such as labour and capital; n = country index; t = time index; gA = growth rate of crop area; gCY = growth rate of crop yield; ε = area price elasticity; γ = yield price elasticity; α = crop area intercept; β = crop yield intercept.

Domestic demand for a commodity is the sum of its demand for food, feed, and other uses (eq. 8). Food demand is a function of the price of the commodity and the prices of other competing commodities, per capita income, and total population (eq. 5). Per capita income and population increase annually according to country-specific population and income growth rates (as shown in eq. 6 and 7). Prices are endogenous in the system of equations for food. Domestic prices are a function of world prices, adjusted by the effect of price policies.

$$\text{Demand for food: } QF_{mi} = \alpha_{mi} \times (PD_{mi})^{\varepsilon_{im}} \times \prod_{j \neq i} (PD_{mj})^{\varepsilon_{jn}} \times (INC_m)^{\eta_m} \times POP_m \quad (5)$$

$$\text{where } INC_m = INC_{t-1,mi} \times (1 + gI_m) \quad (6)$$

$$\text{and } POP_m = POP_{t-1,mi} \times (1 + gP_m) \quad (7)$$

$$\text{Total demand: } QD_{mi} = QF_{mi} + QL_{mi} + QE_{mi} \quad (8)$$

where QD = total demand; QF = demand for food; QL = derived demand for feed; QE = demand for other uses; PD = the effective consumer price; INC = per capita income; POP = total population; FR = feed ratio; FE = feed efficiency improvement; PI = the effective intermediate (feed) price; i, j = commodity indices specific for all commodities; l = commodity index specific for livestock; b, o = commodity indices for feed crops; gI = income growth rate; gP = population growth rate; ε = price elasticity of food demand; γ = price elasticity of feed demand; η = income elasticity of demand; α = food demand intercept; β = feed demand intercept.

Evenson and Rosegrant estimated 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 over the period. Land-saving estimates were higher for rice (7.5 – 9.4%) which was 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 corresponds to 9 – 12 million ha in developed countries and 15 – 20 million ha in developing countries. These **estimates of a total land saving effect from CGI of 24 – 32 million ha between 1965 and 2000** are an order of magnitude lower than those of Nelson and Maredia, but are still significant from the perspective of potentially averted deforestation, biodiversity loss and greenhouse gas (GHG) emissions. Evenson and Rosegrant also use assumptions to apportion part of the land saving to CGIAR CGI research.

While the IMPACT model provides a greater degree of economic realism than estimates based on the global food equation, there are still many restrictive assumptions. First, IMPACT is only a partial equilibrium model for the agricultural sector - it does not compute equilibria for other markets, which misses an entire pathway of impacts via factor markets (labour and capital). Second, the model does not include a land market and lacks any explicit link to the physical realm of existing land cover. In IMPACT, CGI can only ever save land because there is no mechanism for modeling land competition between crop and non-crop uses, and even for crops, the coverage was only partial.

2.2 The land rent effect: Jevon’s paradox

When innovations such as new agricultural technologies that improve productivity or reduce costs for producers, are adopted they increase producers’ profits, at least in the short run. Making agriculture more profitable relative to other land-uses at the margin encourages agricultural area expansion. Therefore it is an apparent paradox that the adoption of a technology that is ostensibly land-saving (i.e., yield increasing) could under some circumstances lead to area expansion.

The general principle of this paradox, a net increase in use of an input when a technology is introduced that increases the efficiency of the same input, was highlighted by Jevons (1865, cited in Alcott, 2005) in the context of aggregate coal use and its relationship to new blast-furnace technologies:

“Economy multiplies the value and efficiency of our chief material...[and] renders the employment of coal more profitable, and thus the present demand for coal is increased. . . . [If] the quantity of coal used in a blast-furnace, for instance, be diminished in comparison with the yield, the profits of the trade will increase, new capital will be attracted, the price of pig iron will fall, but the demand for it increases and eventually the greater number of furnaces will more than make up for the diminished consumption of each”

In the context of agricultural technologies, a result consistent with Jevon’s paradox would be where yields (i.e., land efficiency) increase **and** there is increased expansion of agricultural land. The work by Angelsen and Kaimowitz (2001) incorporates a number of local and national level case-studies, many of which find this kind of result.

Models that make land rents endogenous can simulate how the returns to alternative land-uses, such as agriculture and forest, vary under different scenarios. In a context where agriculture is well integrated in markets, and assuming two kinds of land-use (agriculture and forest) we can model land rents as a function of distance to a forest frontier. In a von Thunen model (after von Thunen, 1826; in Angelsen 2007) land rent from agricultural activities (r) is modeled as a function of distance (d) from a central market and can be computed as a residual as follows (Angelsen 2007):⁶

$$r(d) = py - wl - qk - c - vd \quad (9)$$

where yield is given by y and this output is sold in a central market at price p ; labour (l) and capital (k) required per ha are at prices w (wage) and q (annual costs of capital); the cost of defending property rights is given as c ; and transport costs per km are denoted by v and the distance from the centre as d . Assuming

⁶ This model assumes well functioning markets and profit maximization. More restrictive models are reviewed in Angelsen (1999)

perfect markets and homogenous land quality, then agriculture expands on the frontier until there are zero returns to land (i.e. $r = 0$). That is the distance from the center at equilibrium is given by:

$$d = (py - wl - qk - c)/v \tag{10}$$

Assuming perfectly elastic demand, p is unchanged, and new agricultural technologies that raise yields will tend to promote expansion of the frontier by boosting output (y). New agricultural technologies that reduce costs promote expansion by reducing labour or capital requirements per unit output (l and k respectively). If demand is less than perfectly elastic, both effects could be overruled by reductions in p either locally or globally through trade. The insight gained from a land rent perspective on the kinds of factors that inhibit or promote the expansion of agricultural area are summarised in table 2 below⁷.

The size of the supply shift and the elasticity of demand are the two crucial determinants of the commodity price effect from technological change. The size of the supply shift will be determined by the market share of the adopters and the average treatment effect size of the technology on reducing the per-unit cost of production.

The impact of new technologies on agricultural expansion may also be transmitted through capital and labour markets if the technological change is factor biased. Technological change that increases labour use per hectare has the potential to constrain agricultural expansion through impacts on local labor markets, particularly in forest rich regions with high underemployment of labor where deforestation induced by population growth may be reduced by increased employment. The process of technological change from traditional varieties to modern varieties in the case of the Green Revolution was generally labor saving.

Table 2: Factors promoting and limiting expansion of agriculture at the frontier

Factors promoting expansion	Factors limiting expansion
Higher output prices from increased demand or low supply (<i>increase in p</i>)	Lower output prices from lower demand or high supply (<i>decrease in p</i>)
Lower wages or opportunity costs of labour (<i>decrease in w</i>)	Higher wages or opportunity costs of labour (<i>increase in w</i>)
Lower cost of defending property rights (<i>decrease in c</i>)	Higher cost of defending property rights (<i>increase in c</i>)
Technologies that increase yield (<i>increase in y</i>)	
Technologies that save inputs (<i>decrease in l or k</i>)	
Reduced access costs (<i>decrease in v</i>)	Higher access costs (<i>increase in v</i>)
Lower costs of capital (<i>decrease in q</i>)	Higher costs of capital (<i>increase in q</i>)

Source: Angelsen and Kaimowitz, 2001

The empirical case-studies included in the volume by Angelsen and Kaimowitz (2001) are built around one or more of the above impact pathways. Many studies at the local level present tropical agricultural technologies in a bad light – yield increases for cash crops are not tempered by price reductions, boosting land rents at agriculture-forest frontiers and encouraging agricultural expansion. Clearly, when there is elastic demand combined with spatial bias in favour of adoption at the frontier, we would expect technological change to cause further deforestation. In those cases, the increased profitability effect on demand for land may dominate the output price effect and lead to greater agricultural expansion.” However, in the case of staple crops like rice, wheat, maize and cassava, at a global rather than local level, the impact of widely adopted technologies on land-cover change is likely to be mainly via a

⁷ Note that c can be negative in the case of forests being cleared to establish property rights on untitled land – a situation that is common in Brazil.

suppression of agricultural prices, relative to the counterfactual, that should result in a net land saving in the aggregate.

2.3 Formalizing the two competing perspectives into a single framework

The analytical framework developed by Hertel (2010) allows highlighting the conditions under which agricultural technologies are likely to result on land savings or land expansion. The framework is a partial-equilibrium model of a profit-maximizing farm sector operating under constant returns to scale. Non-land input prices are assumed to be exogenous (long-run closure). The model can be used to gain insights into the effects of technological progress at varying degrees of spatial aggregation (e.g., farm, regional, or global level) by changing its parameters. The model allows for exogenous shocks to output demand, land availability, and yield growth, and is also equipped to deal with technical change.

We follow Hertel's simplistic assumption of yield growth being exogenous to the agricultural sector to show (see Appendix 4 for details) that the percentage change in land rents (p_L) is a function of the demand elasticity for agricultural output (ε_D), land supply elasticity (v_L), the elasticity of substitution among land and non-land inputs (σ), and the share of land in total costs (θ_L). Formally:

$$p_L = \frac{-\Delta_L^D}{v_L + \varepsilon_D \theta_L + \sigma(1 - \theta_L)} \quad (11)$$

All of the parameters in the denominator of (11) are non-negative; thus, an increase in land productivity ($\Delta_L^D > 0$) will result in decreased land rents ($p_L < 0$), with the consequent reduction in land supply, result that can be better appreciated by plugging (11) into the land supply schedule (equation (4A) in Appendix 4):

$$q_L = v_L p_L = v_L \frac{-\Delta_L^D}{v + \varepsilon_D \theta_L + \sigma(1 - \theta_L)}. \quad (12)$$

For a given productivity shock (Δ_L^D), equation (12) shows that the reduction in land rents (p_L), and thus in land supply (q_L), will be greater the smaller the elasticity of demand, ε_D . The elasticity of demand is likely to be larger for small areas well connected to markets than for the entire world. This reinforces the point made by Angelsen, about land savings being conditional on the geographic scope of technical progress. Notice that the elasticity of demand is further diluted by the share of land on total costs ($0 \leq \theta_L \leq 1$), thus, accentuating the land saving effect of small demand elasticities.

The Food and Agricultural Policy Research Institute (FAPRI) data on global elasticities indicate that rice, wheat, maize, barley, sorghum, soybean, and groundnuts (all part of the twenty CGIAR mandate crops) have inelastic demands, in some cases near zero (i.e. no change in quantity demanded from a change in price). Hence, CGIAR-driven technologies that increase total factor productivity in most productive regions of the world are likely to be land-saving. However, small regions selling into large markets (e.g., a small country that sells into international markets) are likely to face larger elasticities of demand and thus the introduction of new technologies may result in increased land rents and thus local land expansion.

Equation 9 also suggests that given productivity shock (Δ_L^D), reductions in land rents are larger the smaller the land supply elasticity, v_L (percentage change in land supply given a 1% in the rental price of land), reflecting that when land supply is inelastic, prices fall faster than quantities. This is because technical progress makes land appear as if it were more abundant (i.e., if land productivity doubles, a single hectare produces the same than two hectares used to produce before the shock), thus, with smaller land supply elasticities, the reduction in land demand implied by increased relative abundance, results in

more than proportional reduction in land prices and consequently, smaller land supply elasticities have a land-saving effect.

Similarly, equation (12) suggests that the reduction in land rents will be greater the smaller the elasticity of substitution (σ) between land and non-land inputs, reflecting the difficulty of bringing more land into production (which would drive land rents up) to substitute for non-land inputs. To see this more clearly, consider the limiting case when land is only a marginal fraction of production costs ($\theta_L \rightarrow 0$). Under this condition, and further assuming unresponsive land supply ($v_L = 0$), the demand elasticity effect vanishes and σ is the crucial factor in determining the sign of p_L , and for a given Δ_L , land rents will be less negative as σ increases. This is because, although land has become more abundant in relative terms (and thus one would expect its price to decrease), higher possibilities of substitution allow farmers bringing more land into production to the expense of non-land inputs, thus driving land rents up. As $\theta_L \rightarrow 1$, the reducing effect of the cost share on the demand elasticity diminishes, and indeed, when $\theta_L = 1$, only land is used in production, hence the effect of the elasticity of substitution is irrelevant.

In his original work, Hertel (2010) relates the role of the different parameters discussed above (demand elasticity, elasticity of substitution between land and non-land inputs, land supply elasticities, and land cost shares) to the land-supply response to changes in commodity prices. The main contribution of Hertel (2010) is to decompose the land supply response to changes in commodity prices into an extensive (physical expansion of the agricultural area) and intensive margin (increased yields from existing agricultural area). The extensive margin is the elasticity of land supply to changes in commodity prices, and is given by:

$$\eta^{ext} = v_L \theta_L^{-1}. \quad (13)$$

So the elasticity of land supply to commodity prices (η^{ext}) is larger than the elasticity of land supply to land rents (v_L) capturing the magnification effect through which changes in output prices are amplified as they are transmitted to the sector-specific factors of production, in this case, land.

The intensive margin captures the increase in productivity by unit of land and is given by:

$$\eta^{int} = \sigma(\theta_L^{-1} - 1). \quad (14)$$

So the ability to intensify production increases with the elasticity of substitution between land and non land inputs (larger σ yields a larger intensive margin response) and decreases with the importance of land in the production cost structure. As discussed above, in the limit, if the only input used into production is land, so that $\theta_L = 1$, there is no margin for intensification.

Hertel (2010)'s long-run land supply response to commodity prices is given by:

$$q_L = - \frac{\Delta_L^D}{1 + \frac{\eta^{int}}{\eta^{ext}} + \frac{\varepsilon_D}{\eta^{ext}}}. \quad (15)$$

The main contribution of this equation is to recognize that agriculture can expand at the extensive margin (physical expansion of the agricultural area) or at the intensive margin (increased yields from existing agricultural area) with the overall effects on land use determined by the ratio of the two. The first ratio η^{int}/η^{ext} captures incentives to expand at the intensive margin. When the opportunity cost of land is high (land scarcity scenario), and η^{int}/η^{ext} is high, this encourages intensification. Conversely, where land is readily available and relatively cheap (low opportunity cost of land), expansion at the extensive margin

occurs. The second ratio of relevance above is ε_D/η^{ext} indicating that response is least where demand is highly inelastic relative to the elasticity at the extensive margin. In the simplest of cases, which corresponds to the Borlaug hypothesis with no supply response and no demand response, $\varepsilon_D = \eta^{int} = 0$, a yield shock, Δ_L^D , results in a proportional change in area of the opposite sign. With $\eta^{int} = \eta^{ext} = \varepsilon_D$ the impacts of a positive yield shock are equally distributed between changes in supply reduction at the intensive margin, changes in supply reduction at the extensive margin, and higher changes in demand (Hertel, 2010).

Empirical estimates of elasticities of land expansion at the margin with respect to prices (η^{ext}) are especially scarce. Hertel (2010) cites low elasticity estimates of 0.025 to 0.033 globally (i.e., for a 10% increase (decrease) in the price of a given commodity, crop area would increase (decrease) by 0.25 to 0.33 percent), but ranging up to 0.90 for Brazil. The size of the elasticity reflects not only land scarcity which tends to increase over time in most countries but also governance factors that may protect available natural areas from agricultural encroachment. Likewise, there are few estimates of the elasticities of intensification (η^{int}) outside of developed countries. They are likely to change over time, depending on exploitable yield gaps. In the USA, Hertel (2010) finds that η^{int} for maize has fallen from 0.7 in the post War period to 0.2 recently.

In summary, this admittedly simplistic framework allows highlighting how the land saving effect of technical progress can be tempered by the geographic scope of technical change, the technological possibilities of substitution between land and non-land inputs, and the share of land in total production costs.

2.4 Estimating impacts using a global CGE model

2.4.1 The GTAP model

For a more comprehensive model we turn to a global model that includes the land rent effects. The Global Trade Analysis Project (GTAP) model is a multi-commodity, multi-regional computable general equilibrium model based on national or regional input-output tables.

Villoria (2011) uses GTAP-AEZ, a version of GTAP which is linked to a global spatially-explicit database on land use (AEZ stands for agro-ecological zone). The foundations of these data are the global datasets for agricultural productivity from Monfreda et al. (2008) and forests from Sohngen et al. (2009). Lee et al. (2005) used these data to develop a land use and land cover database that offers a consistent global characterization of land in crops, pastures, and forestry, taking into account biophysical growing conditions. AEZs represent six different lengths of growing period (6 x 60 day intervals) spread over three different climatic zones (tropical, temperate, and boreal).

The GTAP-AEZ framework used for this work introduces land competition directly into land supply via a two-tiered structure such as that used by Keeney and Hertel (2009). GTAP-AEZ potentially offers some advantages over the IMPACT model discussed earlier;

- The crop coverage is complete in GTAP, although they are aggregated into only five categories complicating the inclusion of specific CGIAR crops. Eighteen agroecological zones are defined, several of which may occur within a country.
- In GTAP-AEZ the land rent effect is incorporated, which then allows us to model the net effect of land-saving minus increased expansion, while also crudely modelling land supply through a constant elasticity of transformation between crop, pasture and forest lands. However, this greater ambition also results in further problems of restrictive assumptions which will need to be addressed in future research.
- GTAP-AEZ uses historical patterns of trade (the Armington assumption) between pairs of countries to influence where expansion and contraction of agricultural area takes place. It is

possible to assess effects across different crops and different global regions, but the main results are reported here are for aggregate results across all developing countries.

- GTAP-AEZ as a computable general equilibrium model allows for general equilibrium effects through not only product markets, but also labor and capital markets.

2.4.2 Simulations of the land-cover impacts of crop germplasm improvement in CGIAR crops

Villoria (2011) uses factor-neutral productivity “shocks” in GTAP-AEZ to replicate the simulations carried out by Evenson and Rosegrant using IMPACT to estimate the land use impacts of crop germplasm improvement in developing countries since 1965. This is done by removing total productivity gains attributable to CGI in the CGIAR focus crops in a “back-casting” experiment. These negative TFP shock to crop productivity allows us to track the main price, production, land use and trade effects.

Since GTAP includes cassava, beans, lentils and potatoes in more aggregate groupings (vegetables), and maize, barley, sorghum and millet in another more aggregate grouping (coarse cereals), we show only results for two cereals – rice and wheat, and coarse grains. For simplicity, only CGI effects are presented in Table 3, although results assuming CGI synergies with other yield changing factors were also computed by Villoria (2011). Overall price effects for rice, coarse grains and maize (as one of the main coarse grains) are large and quite comparable in the two models (Table 3), in despite of fundamental differences on underlying data, product definitions, and fundamental modelling assumptions. In general, GTAP predicts a much larger area effect of 12 to 26 percent on land area expansion (equivalent to a land area savings – for these crops taken in isolation – of more than 75 million ha) than IMPACT (2-4 percent). This is likely due to the much larger coverage of crops in GTAP which allows more scope for crop substitution between those food crops that received the TFP shock and those that did not. However, since most of this land expansion in the GTAP counterfactual is from substitutions for other crops, the overall expansion of crop land is around 2.2%, partly in developing countries where yields are reduced, and partly in developed countries through price and trade effects.

Table 3 – Comparison of results from Evenson and Rosegrant and Villoria estimations

	Evenson and Rosegrant (2003)			Villoria (2011)		
	Model: IMPACT			Model: GTAP-AEZ		
	Time period: 1965 – 2000			Time period: 1965 – 2004		
	TFP shock to CGIAR crops ^a : -0.72% per year (weighted average); -32.2 total TFP shock)			Yield shock to CGIAR crops ^a : -0.72% per year (weighted average); -32.2 total TFP shock)		
	Wheat	Rice	Maize	Wheat	Rice	Coarse Grains ^b
Prices (% change)	+ 29	+80	+23	+29	+68	+20
Area (% change in global harvested area)	+3.2	+7.5	+1.1	+9.4	+20	+8

^a CGIAR crops represented in this weighted TFP shock include: wheat, rice, maize, sorghum, millet, barley, dry beans, lentils, cassava and potato.

^b GTAP-AEZ model includes the following CGIAR crops under this grouping--maize, barley, millet and sorghum.

Additional crop land in GTAP-AEZ can be obtained through conversion of pastures or forests. Table 4 shows that the model estimates the additional land would have relatively more impacts on forests than in pastures. Although these estimates are in terms of productivity weighted land area, they indicate **an expansion in cropland of between 17.9 and 26.7 million ha, of which 12.0-17.7 million ha would**

have been in developing countries. This estimate is strikingly similar to that of Evenson and Rosegrant (24 to 32 million ha globally) despite the differences in the modelling and coverage of crops. Note, that the CGIAR can only claim a portion of this saving, since CGI is the result of both CGIAR and national system investments in crop improvement.

Table 4 - Percent change in land cover assuming no crop germplasm improvement-related productivity gains in CGIAR crops since 1965, GTAP-AEZ estimates

	Cropland	Forests	Pasture
Developing countries	1.52	-0.86	- 0.66
Developed countries	0.87	-0.51	- 0.36

The simulation results from GTAP-AEZ demonstrate that for the staple food crops, as expected, the Borlaug hypothesis prevails - there is land-saving as a result of the global crop germplasm improvement and subsequent increases in yield, that have taken place since 1965. While there is some consistency with the findings of Evenson and Rosegrant (2003) and those of Villoria (2011), the magnitude of all effects is lower, and in both cases orders of magnitude lower than predicted by simple methodology discussed in section 2.1.1 that do not take account of feedback loops through prices of products and land. These lower net land-saving effects may still represent a significant positive impact of agricultural research on the environment. However, the overall effects on land saving are dwarfed by the effects of CGI on food prices. In the absence of CGI in developing countries, increases in food prices of the order predicted by both GTAP and IMPACT would have serious implications for poverty reduction and malnutrition.

2.4.3 Limitations

Overall each generation of estimates of land savings from CGIAR crop intensification has incorporated additional impact pathways through more complex modelling. GTAP-AEZ is one of a number of global economic models of land-use change (reviewed by Hertel et al, 2009) but most others such as IMPACT (Rosegrant, 2002), WATSIM (Kuhn, 2003), AgLU (Sands and Leimbach, 2003) and FASOM (Adams et al, 1996; USEPA, 2005) are partial equilibrium models that do not consider impacts through economy-wide effects, and most importantly for this study, through land market effects.

Very important policy questions regarding the land-use change impacts of alternative policies are being asked of models such as GTAP-AEZ. The effects of biofuel mandates on land use are a particularly prominent example, with much of the recent literature on land-use change being devoted to the question of whether biofuels actually deliver net benefits in terms of GHG emissions when indirect land-use change from higher prices are factored in (e.g., Searchinger, 2008; and the critique of that paper by Keeney and Hertel, 2009).

Nonetheless, the introduction of land heterogeneity (AEZs), pasture and forest land use, and land markets into CGE models is a relatively new enterprise. As such, most of the modelling assumptions need to be validated against observed data. Two assumptions are particularly critical. From the perspective of the demand for land, GTAP-AEZ assumes that there is only one national production function for each crop. From the supply side, GTAP-AEZ assumes a Constant Elasticity of Transformation functional form to determine the transformation of land across different uses in crops, pastures and forests. There are few empirical estimates of these elasticities and they are likely to vary across factor endowments and institutional settings.

Decomposing the impacts on production and trade of the productivity shock to developing country agriculture⁹ GTAP-AEZ estimates that developing countries would have imported 111 % more wheat and

⁹ Remember that developed countries in this counterfactual still benefit from the level of CGI we observe historically.

228 % more rice from developed countries. (Recall that CGI occurs at its historical rate in developed countries – though in fact several studies have documented the significant positive spillover effects of CGIAR research on developed countries, e.g., Pardey et al, 1996). This raises the question of whether this counterfactual scenario would ever have been allowed to play out in practice. It is valid to ask whether the purely economic counterfactuals presented in this paper are ever likely to have occurred from a political perspective: government policy will often exert more influence on outcomes – particularly when related to food concerns – than economic rationality might dictate based on open trade models.

The assumptions can be improved through new empirical evidence on particular elasticities in different contexts, as well as further advancement in the modelling. At the moment, our theoretical understanding of land-use change issues is somewhat ahead of our abilities to make empirical estimates. However, no matter how good the state of the art of modelling becomes, we will always be constrained by the inevitably high degree of uncertainty that we have about the extent to which a model can generate a sound counterfactual back-cast over such a long time period.

3. Expansion at the agricultural frontier

Agriculture competes for land with forest, other kinds of natural ecosystems and urban areas. Most countries have followed a development path that has resulted in significant loss of forest cover from their initial endowment, with conversion to agriculture as the main driver of deforestation and land-cover change. Over the long-run, since 1850, 600 M ha of forest and 470 M ha of savannah have been converted to agriculture, and yet many developing countries are at points on their land-use transitions that are far from a discernible turning point (Geist, 2001). The land-use transition theory (Mather, 1992; Grainger, 1995; Mather and Needle, 1998) describes the long-run reduction in the percentage of land area under forest experienced by every country where there was a majority of forest cover before human settlement. Seen in this light, deforestation is an inevitable feature of national development if a country is to experience a growth in population and living standards (Grainger et al, 2003). A “forest transition” (Chomitz, 2007) takes place when this long-run trend is stabilised and then reversed through net increases in forest area as a result of afforestation or reforestation.

Modern informational tools allow more precise measures of areas deforested as well as their causes. Gibbs et al (2010) using satellite imagery find that the total agricultural area in tropical countries increased by more than 75 M ha during 1980s and 1990s. Fifty-five per cent of this expansion occurred by clearing intact, natural forest, and a further 27 per cent came from expansion into “disturbed forest”. Nearly all of this conversion occurred in developing countries and transitional countries, since forest area is expanding in most rich countries. Moreover, deforestation has been concentrated in a few countries. Hansen et al. (2008) again using satellite imagery, estimate that 48% of all humid tropical forest clearing from 2000 to 2004 occurred in Brazil, followed by 12% in Indonesia, both of which are considered “hotspots” tropical deforestation. Rising interest in global greenhouse gas emissions has put a spotlight on the role of agriculture in tropical deforestation (Burney et al, 2010; West et al, 2010).

Studies at lower levels of aggregation also support the role of agriculture in deforestation. In a meta-analysis of 152 studies at the sub-national level on the causes of deforestation, agricultural expansion was identified as a proximate cause in 96 per cent of all cases (Geist and Lambin, 2001). Very little deforestation occurs without agricultural expansion, for crops and cattle, although there are usually a number of simultaneous causes operating together.

From the 1960s to the 1980s, tropical deforestation for agriculture was driven by population growth as a growing number of farmers pushed further into the frontier in search of land to meet subsistence needs (Rudel et al, 2009). Subsequently, a slowing in the global population growth rate and rapid integration of the global economy, has meant that expansion of commercial agriculture is now recognised as being the main driver of deforestation (Lambin et al, 2001; Nepstad et al., 2006; Rudel et al, 2009a) which in turn is driven by urbanization, rising incomes and increased trade flows (deFries et al, 2010). Africa is the only region where agricultural expansion is still primarily driven by population growth (Chomitz, 2007).

Although agricultural expansion may be the proximate cause, behind this expansion three groups of factors have been identified as the primary drivers in meta analyses of over 140 studies are (i) commodity prices, (2) construction of roads, and (3) low wages or high unemployment (Angelsen, 2010). These factors are in turn highly condition by property rights and governance of forest resources (Chomitz, 2007).

While agriculture is important to deforestation, the corollary does not hold. During the period 1985 – 2004, crop and livestock production grew by 3.3 – 3.4% per annum whereas gross annual deforestation (1990 – 2005) for agricultural uses represented only approximately 0.3% of the total agricultural area (Angelsen, 2010). This suggests that the vast majority of the increase in agricultural output come from sources other than simply expanding into forests.

3.1 Recent market-led commodity expansion

A handful of commodities have been associated with recent land expansion. If we consider the 10 most important commodities of the last 20 years in terms of area expansion in developing countries only, oilseeds led by soybeans and oil palm, and cereals (rice, wheat and maize) dominate. Table 5 shows that average yields have increased across the board, whether the crop is increasing or decreasing in area, which suggests that other factors are more important in determining land-use change than technology (Rudel et al., 2009b). Beyond crop area expansion, the expansion of pastures for cattle has been significant with 12 M ha alone in Brazil over the past 20 years as has plantation forestry.

These changes in crop composition mostly reflects changes in diets towards vegetable oils and livestock products driven by high, sustained rates of economic growth observed in countries like China in the last two decades. A major proportion of soybeans and maize production is destined for animal feed. Moreover, growing proportions of the global soybean, maize, rapeseed, oil palm and sugar cane production are being diverted to fulfil government biofuel mandates (e.g. in the US, EU and Brazil). Some of this expansion is taking place directly in developing countries, explaining for example, the rapid expansion of sugarcane (mostly in Brazil). But indirect effects of expansion in developed countries, maize in the US for example, are likely to be significant (Hertel et al, 2010).

Three commodities stand out for evidence that their expansion over the past 20 years has intersected with tropical deforestation - pastures, soybean, and oil palm.¹⁰ Pastures are not included in table 5 as the data on them held on FAOSTAT are of poor quality. However, were they to be included, the data suggest that in the region of 300 M ha of pastures and meadows have been established in developing countries since 1990.

In this section we examine three commodity-country combinations with respect to evidence on the relative roles of policies and governance versus technologies as drivers of expansion at the forest margin. The three commodities and countries most often ‘blamed’ are: pastures/cattle in Brazil, soybeans in Brazil, and oil palm in Indonesia. Area growth on the frontier associated with these commodities has attracted much research on which this review draws. These changes are also highly relevant to the CGIAR which has through CIAT (pastures) and CIFOR carried out considerable research on the expansion of these commodities (Pacheco et al, 2011; Barona et al, 2010; Sheil et al., 2009).

¹⁰ Section 2 has already reviewed the impacts of technology on land area expansion for rice, wheat and maize.

Table 5: Top 10 most expanded and contracted crops 1990-2007 (Globally and for developing countries only)¹¹ and associated change in global yields

Top 10 most expanded crops						
Globally				Developing countries only		
Rank	Crop	Change in harvested area (M ha)	Change in yields (%)	Rank	Crop	Change in harvested area (M ha)
1	Soybeans	36.9	27.8	1	Soybeans	30.9
2	Maize	23.9	35.1	2	Maize	18.9
3	Rapeseed	11.1	30.8	3	Wheat	12.2
4	Rice, paddy	9.4	20.1	4	Rice, paddy	10.6
5	Oil palm fruit	7.8	43.8	5	Oil palm fruit	7.8
6	Sunflower seed	6.9	-2.4	6	Cow peas, dry	5.7
7	Cow peas, dry	5.7	16.3	7	Sugar cane	5.4
8	Sugar cane	5.5	14.2	8	Potatoes	4.3
9	Cassava	2.9	23.0	9	Seed cotton	3.3
10	Olives	2.9	18.1	10	Cassava	2.9

3.1.1 Pastures

Pastures have expanded by over 40 M ha in Brazil since 1970 as the cattle herd has more than doubled to over 200 million head to meet rising domestic and international markets. Brazil is now the world's largest meat exporter. As a consequence, Brazil has been the world leader in tropical deforestation with an average of about 2 M ha/year cleared between 1996 and 2005 (Nepstad et al, 2009).

The frontier to the Brazilian Legal Amazon¹² since the 1970s has been open for claiming by ranchers, and between the 1970s to the early 2000s, this process was supported by successive Brazilian governments. This support was either explicit in the form of government settlement programs designed to colonise the Amazon, or implicit through a lack of any protection to the region's forests.

Under these circumstances it is not surprising that the beef production system in Brazil has historically been very extensive with extremely poor productivity. There have been few incentives to encourage improved pasture adoption and intensification of grazing. Indeed incentives support expansion at the extensive margin. The Brazilian constitution authorises reassignment of private lands to squatters if the land is not placed into productive use and, in practice, forest lands are not recognised as productive uses (Araujo et al, 2009). The lowest cost means of securing the land through productive use is conversion to pasture for livestock. Historically, the overriding concern of ranchers has been to stock a minimum number of cattle to ensure a level of property rights over public lands that have been appropriated, in the absence of suitable mechanisms for ensuring title and a functioning land market (e.g., Merry et al., 2008)

In all, the evidence reviewed here suggests that improved pastures have not been a driver of deforestation in Brazil to date, as the economic and policy environment has favoured extensive production and this has dominated any technological impacts on land rents. However, there is recent evidence that intensification is now playing a significant role. Pacheco and Pocard-Chapuis (2009) examine changes between two agricultural censuses in 1995/96 and 2006. The growth in beef production during this period is composed

¹¹ The table gives a comparison of 3-year rolling averages for 1989-1991 vs. 2006 – 2008. Developing countries are defined as all countries except for USA, Canada, Europe, and wealthy countries in Asia.

¹² The Brazilian Legal Amazon consists of the following states: Amapá, Amazonas, Rondônia, Roraima, Pará, Maranhão (west of 448W), Tocantins, Goiás (north of 138S), and Mato Grosso

of a simultaneous extensification (expansion of the area of cultivated pasture) and intensification (increase in the stocking rate) as follows. For the Legal Amazon the figures are as follows:

1995/96: 51 million hectares x 0.70 head / hectare = 35.7 million head of cattle

2006: 61 million hectares x 0.92 head / hectare = 56.1 million head of cattle

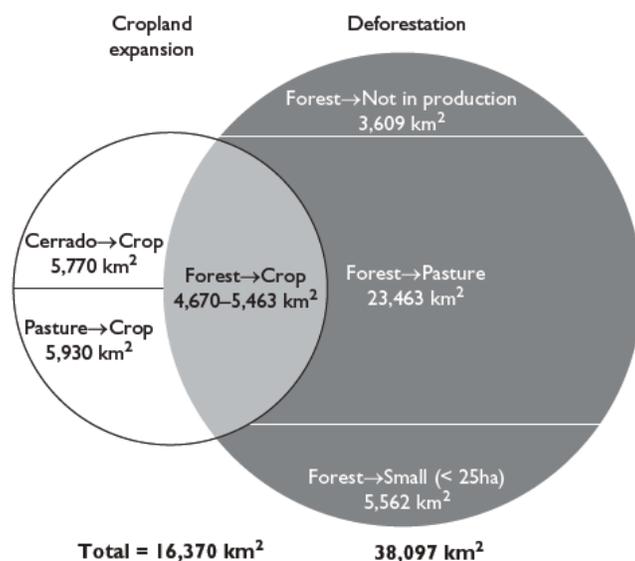
Pacheco and Pocard-Chapuis ask a question of a counterfactual to the observed intensification process, pointing out that if the stocking ratio had stayed at the level of 1995/96, an additional 20 million hectares of pasture would have been needed to produce the same number of cattle. What is not clear is the extent to which: a) improved pastures have supported this increase in stocking density, and b) whether improved pastures may also have increased the rate of expansion by raising land rents.

Four factors now favour intensification of the livestock in addition to any role for improved pastures. First, soybean has much higher gross margins per hectare than livestock ranching as outlined below so is out-competing the more extensive cattle operations in areas where crop production is viable. Second, commercial feedstuffs from by-products from industrial agricultural processing have become commercially available and allow for supplemental feeding at low cost (Frank Merry, personal communication). Third, there is a market-pull effect as both the soy and beef industry attempt to exclude products from newly deforested land from their export supply chains (Nepstad et al, 2009), partly as a response to significant consumer-awareness campaigns by non-governmental organisations such as Greenpeace. Finally, forest governance in the Amazon is improving, in tandem with significantly improved satellite monitoring of new forest clearance, leading to a gradual closing of the forest frontier. With better protection of the Amazon, total area under pasture shows a slight decrease in the 2000s (IBGE - Instituto Brasileiro de Geografia e Estatística website). Deforestation in the Amazon has also slowed dramatically in the period 2005 – 2010 although pasture remains the main source of new deforestation.

3.1.2 Soybean

Brazil is now the world's second largest producer of soybean. Production in Brazil has nearly quadrupled since 1980, and it now accounts for nearly a third of the world's soybean exports (ranking second behind the USA). Although these figures are impressive, the abundance of Brazilian soybeans has come at the expense of pastures as well as millions of hectares of natural vegetation lost over the course of the past three decades. Soybean area in Brazil rose from 8.8 M ha in 1980 to 21.3 M ha in 2008. Since 1990, the fastest growing area for soybean production has been in the Cerrado a frontier area of natural savannah and woodlands. In Mato Grosso the largest state in the Cerrado, cropland expansion (mainly for soybean) into forested areas contributed an average of 17% of the total direct forest loss between 2000 and 2004 (Morton et al, 2006). Most soybean replaced pastures which were directly responsible for over 60 percent of the area deforested (Figure 1, below)

Figure 1: Cropland expansion, deforestation in Mato Grosso, Brazil 2001-04 (Morton et al, 2006)



Barros et al. (2007), describe the factors behind the opening up and settling of the *Cerrado* savannah ecoregion in the 1980s and 1990s, which in turn facilitated soybean area expansion in Brazil over this period. Behind the more proximate factors was a national policy giving significant support to development in the *Cerrado*. Thus, subsidized credit, investments in transportation and storage facilities, energy, extension, rural electrification and mechanization were all supported by government policy.

Technology was also a critical factor in the expansion. Research by EMBRAPA, the widely respected Brazilian Agricultural Research Corporation, initially focused on agronomic methods for soil correction in the *Cerrado* using lime, fertiliser and micronutrients. Subsequently, EMBRAPA's research on soybean from 1975 onwards focused on the adaptation of cultivars to day length of the low latitudes, and to resistance to diseases and pests in this warmer and more humid environment (Barros et al, 2007). Between 1990 and 2010, soybean yields in the *Cerrado* states increased from 2.0 tonnes / ha to 3.0 tonnes / ha (in Mato Grosso) and from 1.6 tonnes / ha to 3.1 tonnes / ha (in Mato Grosso do Sul – data from IBGE website, August 2010). Since 2000, genetically modified herbicide tolerant soybean varieties (“Roundup Ready” – resistant to Glyphosphate-based herbicides) have expanded rapidly to reach 70% of total production in Brazil and greatly facilitated the adoption of cost-reducing zero tillage (Tollefson, 2010).

Availability of more adaptable, higher-yielding and cost saving soybean technologies in Brazil undoubtedly exerted direct pressure on agricultural land expansion. Land prices have risen sharply consistent with expansion based on land rental value associated with adoption of new technologies (Nepstad et al., 2006; Sauer, 2011). Ferraz (2001) found that expansion of crop area was determined by changes in land prices (likely related to improved technologies), government agriculture credit and roads. His findings are consistent with others in concluding that a combination of government policies and technologies encouraged expansion.

Brazil is a major player in global soybean markets accounting for 31 percent of exports¹³, so increased production as a result of the adoption of new technologies would have depressed world price for soybeans and at least partly offset the effect of technology on land rents. The only empirical study to look specifically at the effect of technological change in agriculture on deforestation in Brazil in a general equilibrium market context is Cattaneo (2001) who finds that technological change in soybean increases deforestation. Importantly, however, the model does not allow higher Brazilian production to feed back into international soybean prices (i.e. it makes the “small country” assumption hardly appropriate for

¹³ FAOStat data, 3-year rolling average 2006-2008, soybean exports by value

Brazilian soybeans) which precludes the possibility of a long-run land-saving effect, an effect we model below in Section 3.2.

There has been a gradual move northward of the soybean production frontier, from the Cerrado to the fringes of the Amazon (Barona et al, 2010). This has taken place as a result of some direct deforestation by soybean farmers but mainly from the displacement of cattle ranching by soybean farming. This hypothesised “displacement deforestation” (Barona et al, 2010) is an example of indirect land-use change from soybean expansion, and is analogous to the phenomenon that has gained a lot of attention in recent years with regards the indirect land use impacts of biofuels (Searchinger, 2008; Hertel et al., 2010). While it would be unfair to attribute too much of the negative impact (in terms of biodiversity and greenhouse gas emissions) resulting from this spatial shift north towards the Amazon to the profitability and feasibility of soybean cultivation (rather than, for example, inadequate forest governance and the speculative land clearance behaviour of ranchers) it is a valid question to ask whether this shift would have taken place in the absence of technological change in soybean production.

The fact that the new soybean varieties had a spatial bias towards extending the range of soybean farming northwards suggests that technology has certainly been a factor and pushing out the land frontier, some of it at the expense of tropical forests. But this has to be balanced against the higher prices for soybean that would have prevailed in the absence of technological change, which may have also stimulated soybean expansion. Evidence supports a relatively elastic acreage response of soybean area to future prices of approximately 1 in the Cerrado states, and 0.6 nationally. The elasticity for total crop area response to soybean futures price is approximately 0.3 (Almirall, 2009). Ultimately, the unrelenting growth in demand for soybean is the main underlying driver, swamping the technological effects in its importance.

3.1.3 Oil Palm

Oil palm is especially suited for growing in the humid tropics with a high overlap with tropical humid forests that are valued for their unique biodiversity and for mitigation of climate change. For this reason, the CGIAR has had research interests in oil palm, largely from the perspective of forest policy (e.g. Schoneveld, 2010; Danielsen et al, 2008).

Malaysia pioneered the commercial oil palm industry (Martin 2003, Rasiah 2006). With rising land and labour costs, the industry moved to neighbouring Indonesia, which at 16.9 Mt in 2008 is now the world’s largest producer, slightly ahead of Malaysia (15.8 Mt). Together Malaysia and Indonesia now account for over 85 percent of global palm oil production. Planted area in Indonesia increased five times between 1991 and 2008, from about 1.3 M ha to 6.3 million ha. Investment by large companies in mills and an associated production feedstock area has spurred this expansion.

The oil palm sector has been criticized for being a major contributor to deforestation and greenhouse gas emissions. Land use change and deforestation are the largest single contributors to Indonesia’s greenhouse gas emissions. Some 70 percent of Indonesia’s oil palm plantations (4.2 million ha) are on land previously part of the forest estate (World Bank, 2010). Accounting for crop substitution, Koh and Wilcove (2008) estimate that 55-59% of expansion in Malaysia was on forest land and 56% of the much larger expansion in Indonesia.¹⁴ However, even ignoring crop substitution, oil palm could not have accounted for more than 10 percent of forest loss in Indonesia, where arable land and area under oil palm each expanded by about 3.8 M ha from 1991-2007, while 30 M ha of forest area was lost.

Poor forest governance is a major factor in forest loss in Indonesia. To help expand production, the Indonesian government provided land, in many cases still forested, for nominal fees. Timber sales were often used to finance planting and oil palm establishment. Nonetheless, a considerable area of forest land has been allocated to oil palm and deforested but not planted (Fargione et al., 2008; Sheil et al., 2009; Friends of the Earth, 2009). Many companies allegedly use fictitious palm oil schemes to obtain logging licenses without ever establishing oil palm estates; by some estimates up to 12 million ha have been

¹⁴ In a closer look based on satellite imagery, the report by WWF-Indonesia (2008) shows that in the District of Riau, Sumatra, there was a 4.2 m ha decrease in forest area (nearly all above 40 % canopy closure) from 1981 to 2007, equivalent to a 65% decline in forest area. Oil palm accounted for one third of this conversion with large shares converted by timber extraction and to waste land.

allocated to oil palm and deforested but not planted (Fargione et al., 2008). Casson (1999) found that only 1.4 M ha of 9 M ha concessions had been developed by 1998. The main motivation for this forest loss has been timber extraction - it has been easier to obtain concessions for forest lands for oil palm than for logging.

There is little sign that oil palm expansion is slowing. Vegetable oil markets remain buoyant and demand for feedstocks for biodiesel is picking up. Well publicized risks of establishing oil palm in forested areas in terms of greenhouse gas (GHG) emissions and biodiversity loss imply that ways to improve productivity on already cultivated land are of particular relevance to relieve pressure on forests. However, higher yields will also improve oil palm profitability and provide further incentives to expand at the margin without proper safeguards on forest resources (Swarna Natha and Tisdell, 2009). Yields of palm oil have been stagnant in Indonesia¹⁵. Even with good prospects to increase oil palm yields through improved management¹⁶, it is unlikely that they will be achieved while a set of incentives, that provides cheap land relative to its true opportunity costs, encourage area expansion rather than intensification. A number of policy reforms could help internalize the costs of land expansion and encourage intensification.

- *Market certification.* Responding to the controversies around oil palm and its threat to tropical forests, the industry initiated the Round Table on Sustainable Palm Oil in 2004 to develop and implement palm oil certification. Certification bans plantings that “replace primary forest or any area containing one or more High Conservation Values.”
- *Payments for environmental services.* The valuation of carbon (C) sequestration in tropical forests and the potential of REDD to compete with oil palm has been the subject of several studies. While REDD does reduce the incentives to clear forests, it is by no means clear that it will be enough to compete with oil palm, except in peat lands. Much depends on the price of C, which varies widely by market segment. One recent study estimates that a carbon price of \$22 per tonne would be needed to make forest conservation competitive with oil palm, well above current market values (World Bank, 2010).
- *Regulation through land use zoning.* Environmental costs can be reduced, by developing oil palm on degraded forests and *imperata* grasslands (*alang alang*) usually portrayed as unproductive wasteland. Costs of establishing oil palm on these lands are much lower than on forest lands, and yields are indistinguishable from those on forest land (Fairhurst and McLaughlin 2009). However, as local people and communities may already use degraded lands, bringing these into production will require recognizing such rights and negotiating and sharing benefits with locals. NGOs are implementing demonstration activities that can provide important lessons.

Research by CIFOR on expansion of plantation forestry in Sumatra, has demonstrated that just better implementation of existing policies and regulations can significantly slow deforestation (Raitzer, 2010). Given that oil palm expansion is governed by the same policies, it is likely that these findings also hold for oil palm as well.

¹⁵ This situation, of stagnant yields in the major producing countries in South-East Asia, is still consistent with a global increase in yields between 1990 and 2007 (as shown in table 5). This is due to a shift over time from area under oil palm being dominated in 1990 by Sub-Saharan Africa (53% of total global area), to a situation where the higher-yield South-East Asian countries dominated oil palm area by 2007 (64% of total global area). Over the same period, South-East Asia yields have remained higher than those for SSA by a factor of at least 4. (All calculations based on FAOstat data).

¹⁶ A variety of reasons explain yield gaps—nutrient management, harvesting time, age of plantation, canopy management, and weed and pest control. On smallholdings there is an additional yield gap due to use of poor genetic stock and inadequate fertilizer use. Recent initiatives are testing Best Management Practices (BMPs) on a commercial scale. Initial results have achieved an average of 7 t/ha in 2007 although this is only 15% above previous yields on those plantations (Donough, no date). For the medium term, there is potential to exploit the yield gap between current yields and what could be economically attained. Jalani et al. (2002) puts attainable yields of 6.3-9.5 t/ha. Shiel et al (2009) note commercial potential of 6-7 t/ha so there is a yield gap of 40-50%. The best managed plantations are already obtaining yields of 6.5 to 7.5 t/ha (Wahid, 2004) and up to 10 t/ha have been achieved on commercially managed plots.

3.2 Intensification of oilcrops: A further application of the GTAP model

Soybean in Brazil and oil palm in Indonesia provide a good opportunity to test whether the land rental effects of technological change at the country level might outweigh the land saving effect on increasing yields. Although both Indonesia and Brazil are major exporters, they face highly elastic demand in world markets due to strong potential for substitution among vegetable oils and among exporters. To estimate the magnitude of the two effects, we again applied the GTAP-AEZ model. In the case of soybeans, yields increased by 57% in Brazil from 1990 to 2004¹⁷ and most evidence indicates that gains in TFP are at least of this level. Applying the counterfactual of no TFP increase, area under soybean in Brazil declines by 18 percent and production by 67%¹⁸ due to lower profitability and reduced land rents. This translates into an overall decline in Brazilian crop land of about 300,000 ha with forest area **increasing** by 0.1% and pastures 0.13%. Thus within Brazil, the land rental effect dominates the land saving effect. However, despite a highly elastic export demand for soybeans for world markets in general equilibrium (-2.5), crop land in the rest of the world expands due to higher soybean prices (2%) with an overall crop area expansion globally of about 1.2 M ha. Thus globally the price effect of lower yields considerably outweighs the depressed area in Brazil due to the land rental effect, although overall land saving effects are small.

Similar results were obtained for oil palm. However, in this case, yields have been stagnant for the period of review, so we simulated the effects of a 57% TFP *increase*¹⁹, the mirror image of the soybean case. That is we ask what would have happened to land use, had oil palm productivity increased at the rate of soybean in Brazil—an important question given recent calls to increase oil palm yields to save forests (e.g. Koh, 2007). With higher land rents due to technological change, crop area in Indonesia/Malaysia *expands* by 100,000 ha all of it from forest land, again supporting the importance of the land rental effect. However, globally crop area falls by 500,000 ha, and is partly replaced by forests. Of course, these estimates do not take account of the relative value of highly biodiverse tropical forests in Indonesia / Malaysia relative to possibly less valuable forests elsewhere.

The bottom line is that even with highly elastic demand, the land rental effects of technological change locally are more than compensated globally in a globally integrated market economy that allows for trade. Given that we examined technological changes on the frontier in specific countries, the results suggests that land saving effects of technological change will nearly always dominate land rental effects, except for very localized technological adoption.

4. Implications for the CGIAR

4.1 Higher agriculture yields: necessary, but not sufficient for saving forests

Clearly, raising the aggregate supply in the breadbasket regions of virtually all of the CGIAR mandate crops such as rice, wheat, sorghum and millet through successful research is likely to contribute to reducing agricultural expansion and forest loss. However, the magnitude of the effect is likely to be much less than commonly cited from the simplistic application of the method used by Borlaug. Our best estimate is that global land saved from research on CGI for food crops in developing countries over the period, 1965-2004, is of the order of 30 M ha. While this is significant, the impacts are small relative to the huge impacts of the same research on lowering food prices and ultimately reducing poverty and hunger.

We need to also recognize that research that improves the profitability of agriculture in places with remaining forests may promote greater deforestation by raising the returns to land in agricultural uses relative to returns to forest uses. There is some evidence of such local impacts on the forest margins, although rarely from CGIAR mandated crops. But even for the non-CGIAR mandated crops that are

¹⁷ This translates to a 55% shock variable after adjustment of the TFP with the market share of soybean in Brazil's oilseed market.

¹⁸ It should be remembered that soybean belongs to the oilseed aggregate commodity category in GTAP, and in reality the discussion of land saving or expansion from Villoria's results refer to oilseeds rather than "soybean" per se.

¹⁹ After accounting for the share of oil palm in 'oilseeds sector' this represents about 46% TFP shock in this region.

expanding rapidly on the forest margin (soybean and oil palm), the land rental effect within the country was outweighed by land saving effects in other countries through integration in global markets.

It is important that claims of the land saving effects of new technologies be carefully scrutinized, especially as many scientists continue to argue that they are saving forests through intensification (Grabowski et al, 2011 is a very recent example). In particular, it is critical to distinguish between adoption of new technologies over large areas of intensive agriculture (e.g. Green Revolution technology), and adoption of technologies in frontier areas, which contribute a relatively small share of total global production but may have significant effects on local forests (though small globally). Technologies that improve the productivity of traditional agricultural regions and that are relatively labour intensive show the most promise of saving land and reducing deforestation.

We should also recognise that the impact of technological change on land-saving is likely to be a *weak* effect when compared with the range of other exogenous factors driving land-use change and deforestation. Even for rapidly expanding commodities on the forest margin, such as pastures, soybeans and oil palm, the effects of technological change through returns to land are likely to be much smaller than effects through better governance of land and forest resources. That is, expansion at the intensive margin through new technologies is unlikely to succeed if it is cheaper to expand at the extensive margin where forest land is readily available and poorly governed. Socially, of course, expansion at the extensive margin usually does not consider the real value of forest resources foregone. Recent experience with better governance and monitoring of the Brazilian Amazon and related land uses has shown a dramatic drop in rates of deforestation, even as commodity prices have risen sharply in the past five years.

Land-cover change remains a dynamic process with a lot of potential for further deforestation to take place to meet the projected demands of a growing population, rising incomes and structural changes in diets, and new demands from biofuels (see annex 2). Conversion of natural grasslands and woodlands is likely to have lower costs in terms of ecosystem services foregone, than conversion of tropical forests with high conservation values, carbon storage and other services. Agro-ecological modelling of land suitability by IIASA (International Institute for Advanced Systems Analysis) has identified 1,210 M ha of land that is still potentially suitable for conversion to rain-fed agriculture (Table 6). Well over half of this is forested with two thirds in tropical areas. However, about 450 M ha is savannah or woodlands suited to crop agriculture, with two thirds of this located in sub-Saharan Africa and Latin America. The technological and governance challenge is how to steer further agricultural expansion to these areas where environmental costs will be lower.

Table 6: Existing land use and uncultivated low density areas suitable for cultivation. Regional totals and individual countries with over 10 M ha of nonforest or forest land (shaded) suited to cultivation

	Existing land cover		Uncultivated and suitable for cultivation	
	Forest area	Cultivated area	Forest area < 25 pers/km ²	Nonforest area < 25 pers/km ²
<i>Sub-Saharan Africa</i>	509	210	163	201
Sudan	9.9	16.3	3.9	46.0
DR Congo	148	14.8	75.8	22.5
Mozambique	24.4	5.7	8.3	16.3
Madagascar	12.7	3.5	2.4	16.2
Chad	2.3	7.7	0.7	14.8
Zambia	30.7	4.6	13.3	13.0
Congo Rep	23.1	0.5	12.4	3.5
Angola	57.9	2.9	11.5	9.7
<i>Latin America</i>	934	162	291	123
Brazil	485	62.3	130.8	45.5
Argentina	33.6	28.2	16.2	29.5
Peru	68.3	3.8	40.0	0.5
Colombia	64.5	7.3	31.3	5.0
Bolivia	54.3	2.9	21.0	8.3
Paraguay	19.1	5.4	10.3	7.3
<i>Eastern Europe and Central Asia</i>	885	252	140	52.4
Russia	808	120	129	38.4
East, South and SE Asia	494	445	46.3	14.3
Indonesia	95.7	32.9	24.8	10.5
<i>Rest of World</i>	863	359	135	50.9
Australia	88.1	45.7	17.0	26.2
USA	299	175	74.4	8.8
Canada	308	50.3	30.1	8.7
World Total	3,706	1,503	775	446

Source: Deininger and Byerlee, 2011

4.2 Priorities for the CGIAR

What can the CGIAR do to ensure that it maximizes its potential positive impact on the issue of global land-use change? There are implications for both the generation of new agricultural technologies and for policy research.

At the aggregate level, since food demand is generally inelastic, research on food staples should contribute to meeting growing food demand and forest conservation. Food price effects and labor absorption resulting from technological change²⁰ are likely to reduce agricultural land use in forest margin areas. CGIAR technologies that are widely adopted in developing countries will typically have a large impact on market prices and this will reduce land expansion over what would otherwise occur.

Failure to move towards a sustainable agricultural intensification path would inevitably lead farmers to expand into fragile margins. But if the returns to investment in new land clearing is perceived to be more productive than deepening the investment in the existing land (intensification), and there are relatively few impediments to opening up new land, then expansion occurs. This supports the findings from a number of studies by the ASB partnership – that intensification of agriculture is a necessary but not sufficient condition for forest protection (Minang, 2010). Land-saving technological change on existing agricultural lands needs to work alongside governance interventions such as forest protected areas (Nelson and Chomitz, 2009) and incentive systems such as REDD+ may ensure a win-win model of maximising agricultural productivity and maximising biodiversity conservation. However, tradeoffs between these two objectives are a more likely scenario (Lee and Barrett, 2001) and a priority for the CGIAR should be to help analyze such tradeoffs and promote policy dialogue around them.

CGIAR research on land use and forest policies could potentially have even larger impacts. CGIAR scientists are already very influential in the literature on land-use change. Arild Angelsen carried out much of his research on this topic while he was at CIFOR, and there remains strong research interest at that Centre on the relationship between agriculture expansion and deforestation (e.g. Schoenveld, 2010; Pacheco et al, 2011; Shiels et al., 2009). IFPRI scientists also contribute their expertise to research studies on, for example, the question of whether forest protected areas are actually effective (Andam et al, 2008). The Alternatives to Slash and Burn (ASB) partnership for the tropical forest margins also have research and outreach interests in this area (Minang, 2010). This is an area in which the CGIAR has a comparative advantage, reaching across agricultural and forestry expertise, and the forthcoming Consortium Research Program Portfolio should ensure that these interests flourish.

Improving our understanding of the links between agricultural expansion and forests will not only depend on better micro level studies but also on better macro models especially since international trade features strongly in many of the “blame commodities”. The models presented in this review help in thinking about the range of possible pathways between agricultural research and agricultural expansion, but the uncertainty about many of the parameter estimates and the occasionally ad-hoc assumptions required to connect global land-use data and global economy models, suggest that we are still some way away from having robust models and parameters that capture the complexities of these pathways. Fortunately, this is a very dynamic literature driven largely from outside the CGIAR community. If CGIAR scientists can develop appropriate partnerships, they will have much better models and a broader empirical base to draw on for future assessments of their research impacts.

More generally, the CGIAR needs to better position itself with respect to the global debate on land resources including the extent of land scarcity, the synergies and tradeoffs between agricultural and forest land uses, and the recent rising global interest in private investment in farmland in land abundant countries of Africa and Latin America. Much of this work is being led from outside the CGIAR, but has major implications for how the CGIAR sets its priorities. Through partnership with leading think tanks in this area, the CGIAR should be able to tap into a rapidly expanding knowledge base.

²⁰ Labour shortages and/or higher wages constrain any expansion, but labour saving technologies will foster greater migration to the frontier.

References

- Adams, D. M, Alig, R. J, Callaway, J. M., McCarl, B.A., and S.M. Winnett (1996) *The Forest and Agriculture Sector Optimization Model (FASOM): Model structure and policy applications*. USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon. Research paper PNW-RP-495. 60 p.
- Alcott, B. (2005). Jevons' paradox. *Ecological Economics*, 54(1), 9-21
- Almirall, C. (2009). *Biofuels and Land Use Change: Sugarcane and Soybean Acreage Response in Brazil*. Working paper, Department of Agricultural and Resource Economics, University of California, Berkeley, USA.
- Andam, K.S., Ferraro, P.J., Pfaff, A., Sanchez-Azofeifa, G. and J.A. Robalino (2008) Measuring the effectiveness of protected area networks in reducing deforestation. *Proceedings of the National Academy of Sciences*, 105 (42): 16089-16094.
- Angelsen, A. (1999) Agricultural expansion and deforestation: modelling the impact of population, market forces and property rights. *Journal of Development Economics*, 58: 185–218
- Angelsen, A. (2007). *Forest cover change in space and time: Combining the von Thünen and forest transition theories*. World Bank Policy Research Working Paper 4117.
- Angelsen, A. (2010). Climate Mitigation and Agricultural Productivity in Tropical Landscapes Special Feature: Policies for reduced deforestation and their impact on agricultural production. *Proceedings of the National Academy of Sciences of the United States of America*, 2010
- Angelsen, A., & Kaimowitz, D. (2001). *Agricultural technologies and tropical deforestation* (p. 422). Wallingford, Oxon: CABI Publishing.
- Araujo, C., Araujo Bonjean, C., Combes, J-L., Combes Motel, P. and E.J. Reis Property rights and deforestation in the Brazilian Amazon. *Ecological Economics*, 68: 2461-2468.
- Barona, E., Ramankutty, N., Hyman, G., & Coomes, O. T. (2010). The role of pasture and soybean in deforestation of the Brazilian Amazon. *Environmental Research Letters*, 5(2), 024002. doi: 10.1088/1748-9326/5/2/024002.
- Borlaug, N. (2007). Feeding a hungry world. *Science (New York, N.Y.)*, 318(5849), 359. doi: 10.1126/science.1151062.
- Burney, J. a, Davis, S. J., & Lobell, D. B. (2010). Greenhouse gas mitigation by agricultural intensification. *Proceedings of the National Academy of Sciences of the United States of America*, 1-6. doi: 10.1073/pnas.0914216107.
- Cattaneo, A. (2001) Deforestation in the Brazilian Amazon: Comparing the impacts of macroeconomic shocks, land tenure, and technological change. *Land Economics* 77: 219–240.
- Chomitz, K. M. (2007) At loggerheads? Agricultural expansion, poverty reduction and environment in the tropical forests.
- Christiaensen, L., Demery, L. and J. Kulh (2010) The (evolving) role of agriculture in poverty reduction—An empirical perspective, *J. Dev. Econ.*, doi:10.1016/j.jdeveco.2010.10.006

- Danielsen, F. Beukema, H., Burgess, N.D., Parish, F., Bruhl, C.A., Donald, P.F., Murdiyarso, D., Phalan, B., Reijnders, L., Struebig, M., and E.B. Fitzherbert (2008) Biofuel plantations on forested lands: double jeopardy for biodiversity and climate. *Conservation Biology*, 23 (2): 348-358.
- DeFries, R. S., Rudel, Thomas, Uriarte, M., & Hansen, Matthew. (2010). Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nature Geoscience*, 3(3), 178-181. Nature Publishing Group. doi: 10.1038/ngeo756.
- Deininger, K. and D. Byerlee (2011) *The rise of large farms in land abundant countries: Do they have a future?* The World Bank Development Research Group: World Bank, Washington D.C.
- Evenson, R. E. and D. Gollin (Eds.) (2003) *Crop variety improvement and its effect on productivity: The impact of international agricultural research*. Wallingford, Oxon: CABI Publishing.
- Evenson, R. E., & Rosegrant, M. (2003). The economic consequences of crop genetic improvement programmes. In R. E. Evenson & D. Gollin (Eds.), *Crop variety improvement and its effect on productivity* (pp. 473-497). Wallingford, Oxon: CABI Publishing.
- Ferraz, C. (2001) *Explaining agriculture expansion and deforestation: Evidence from the Brazilian Amazon – 1980/98*. IPEA Working Paper, Rio de Janeiro, Brazil.
- Geist, H.J. and Lambin, E.F. (2001) *What Drives Tropical Deforestation? A meta-analysis of proximate and underlying causes of deforestation based on subnational case study evidence*. LUCC Report series no. 4. CIACO: Louvain-la-Neuve, Belgium.
- Gibbs, H. K., Ruesch, a S., Achard, F., Clayton, M. K., Holmgren, P., Ramankutty, N., et al. (2010). Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proceedings of the National Academy of Sciences*, 1-6. doi: 10.1073/pnas.0910275107.
- Gollin, D. (2010). *Chapter 73 - Agricultural Productivity and Economic Growth. Handbooks in Economics* (1st ed., Vol. 4, pp. 3825-3866). Elsevier B.V. doi: 10.1016/S1574-0072(09)04073-0.
- Grainger, A. (1995) The forest transition: an alternative approach. *Area* 27, 242 – 251.
- Grainger, A. (2003). The impact of changes in agricultural technology on long-term trends in deforestation. *Land Use Policy*, 20(3), 209-223. doi: 10.1016/S0264-8377(03)00009-7.
- Green, R. E., Cornell, S. J., Scharlemann, Jörn P W, & Balmford, A. (2005). Farming and the fate of wild nature. *Science (New York, N.Y.)*, 307(5709), 550-5. doi: 10.1126/science.1106049.
- Hansen, M.C., Stehman, S.V., Potapov, P.V., Loveland, T.R., Townshend, J.R.G., DeFries, R.S., Pittman, K.W., Arunarwati, B., Stolle, F., Steininger, M.K., Carroll, M. and C. DiMiceli (2008) Humid tropical forest clearing from 2000 to 2005 quantified by using multitemporal and multiresolution remotely sensed data. *Proceedings of the National Academy of Sciences*, 105 (27): 9439–9444.
- Haggblade, S., Hazell, P. and J. Brown (1989) Farm - nonfarm linkages in rural Sub-Saharan Africa. *World Development*, 17: 1173-1201
- Hertel, T. W., Rose, S., and R. Tol (2009). Land use in computable general equilibrium models: An Overview. In *Economic Analysis of Land Use in Global Climate Change Policy*, Routledge Explorations in Environmental Economics. United Kingdom: Routledge.

- Hertel, T. W. (2010) *The Global Supply and Demand for Agricultural Land in 2050: A Perfect Storm in the Making?* Presidential address: American Agricultural Economics Association meetings, Denver, CO. GTAP Working Paper No. 63.
- Hertel, T. W., Golub, A. a, Jones, A. D., O'Hare, M., Plevin, R. J., & Kammen, D. M. (2010). Effects of US Maize Ethanol on Global Land Use and Greenhouse Gas Emissions: Estimating Market-mediated Responses. *BioScience*, 60(3), 223-231. doi: 10.1525/bio.2010.60.3.8.
- Keeney, R. and T. W. Hertel (2009) The indirect land use impacts of United States biofuel policies: The importance of acreage, yield, and bilateral trade responses. *American Journal of Agricultural Economics*, 91 (4): 895 – 909.
- Koh, L.P (2007) Potential habitat and biodiversity losses from intensified biodiesel feedstock production. *Conservation Biology*, 21: 1373-1375.
- Koh, L.P and D.S. Wilcove (2008) Is oil palm agriculture really destroying tropical biodiversity? *Conservation Letters*. 1 (2): 60-64.
- Kuhn, A. (2003) *From world market to trade flow modelling – the re-designed WATSIM model*. Final report, Institute of Agricultural Policy, Market Research and Economic Sociology.
- Lambin, E., Turner, B., Geist, H., Agbola, S., Angelsen, a, Bruce, J., et al. (2001). The causes of land-use and land-cover change: moving beyond the myths. *Global Environmental Change*, 11(4), 261-269. doi: 10.1016/S0959-3780(01)00007-3.
- Lee, D.R. and C.B. Barrett (Eds.) (2001) *Tradeoffs or synergies? Agricultural intensification, economic development and the environment*. CABI: Wallingford, Oxon.
- Lee, H., Hertel, T. W., Sohngen, B., & Ramankutty, N. (2005). *Towards An Integrated Land Use Data Base for Assessing the Potential for Greenhouse Gas Mitigation* (No. 25). GTAP Technical Paper (p. 83). IN, USA: Center for Global Trade Analysis, Dept. of Agricultural Economics, Purdue University.
- Mather, A.S. (1992) The forest transition. *Area*, 24: 367-379.
- Mather, A.S. and C.L. Needle (1998) The forest transition: a theoretical basis. *Area*, 30 (2), 117-124.
- Merry, F., Amacher, G. and E. Lima (2008) Land values in frontier settlements of the Brazilian Amazon. *World Development*. 36 (11): 2390-2401.
- Minang, P.A. (2010) *REDD+ and agricultural drivers of deforestation*. Learning event at Forest Day 4, UNFCCC COP 16 , Cancun Mexico, December 5, 2010.
- Monfreda, C., Ramankutty, Navin, & Foley, Jonathan a. (2008). Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical Cycles*, 22(1), 1-19. doi: 10.1029/2007GB002947.
- Morton, D. C., DeFries, R. S., Shimabukuro, Y. E., Anderson, L. O., Arai, E., Bon Espirito-Santo, F. del, et al. (2006). Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *Proceedings of the National Academy of Sciences of the United States of America*, 103(39), 14637-41. doi: 10.1073/pnas.0606377103.

- Nelson, M. and M. Maredia. 2001. Environmental Impacts of the CGIAR: An Assessment. TAC Secretariat Report No: SDR/TAC:IAR/01/11 May 2, 2001. Washington, D.C.
- Nelson, A. and K.M. Chomitz (2009) *Protected area effectiveness in reducing tropical deforestation: A global analysis of the impact of protection status*. Evaluation Brief 7. World Bank: Washington, D.C.
- Nepstad, D.C., Strickler, C. and O. Almeida (2006) Globalization of the Amazon soy and beef industries: opportunities for conservation. *Conservation Biology* 20:1595–1603.
- Nepstad, D., Soares-Filho, B.S., Merry, F. Lima, A., Moutinho, P., Carter, J., Bowman, M., Cattaneo, A. Rodrigues, H., Schwartzman, S., McGrath, D.G., Stickler, C.M., Lubowski, R., Piris-Cabezas, P., Rivero, S., Alencar, A., Almeida, O. and O. Stella (2009) The end of deforestation in the Brazilian Amazon. *Science*, 326: 1350-1351.
- Pacheco, P. and R. Pocard Chapuis (2009) *Cattle ranching development in the Brazilian Amazon: Emerging trends from increasing integration with markets*. Bogor, Indonesia: Center for International Forestry Research.
- Pacheco, P., Aguilar-Støen, M., Börner, J., Etter, A., Putzel L. and M. Vera Diaz (2011) “Landscape Transformation in Tropical Latin America: Assessing Trends and Policy Implications for REDD+” *Forest*, 2(1), 1-29; doi:10.3390/f2010001
- Pardey, P. G., Alston, J. M., Christian, J. E., & Fan, S. (1996). “*Hidden harvest: U.S benefits from international research aid*” International Food Policy Research Institute: Washington D.C.
- Raitzer, D.A. (2008) *Assessing the impact of CIFOR’s influence on policy and practice in the Indonesian pulp and paper sector*. Impact Assessment Paper: CIFOR, Bogor, Indonesia.
- Renkow, M. (2010) *Assessing the environmental impacts of the CGIAR research: Toward an analytical framework*. Working paper for the CGIAR Standing Panel on Impact Assessment. CGIAR Independent Science and Partnership Council Secretariat: Rome.
- Renkow, M. and D. Byerlee (2010) The impacts of the CGIAR: A review of recent evidence. *Food Policy*, 35 (5), 391- 402.
- Rosegrant, M., S. Meijer, and S. Cline. 2002. International model for policy analysis of agricultural commodities and trade (IMPACT): Model description. Washington, DC: International Food Policy Research Institute.
- Rudel, T. K., Defries, Ruth, Asner, G. P., & Laurance, W. F. (2009). Changing drivers of deforestation and new opportunities for conservation. *Conservation biology : the journal of the Society for Conservation Biology*, 23(6), 1396-405. doi: 10.1111/j.1523-1739.2009.01332.x.
- Rudel, T. K., Schneider, L., Uriarte, M., Turner, B. L., DeFries, R., Lawrence, D., et al. (2009). Agricultural intensification and changes in cultivated areas, 1970-2005. *Proceedings of the National Academy of Sciences of the United States of America*, 106(49), 20675-80. doi: 10.1073/pnas.0812540106.
- Sands, R. D. and M. Leimbach (2003) Modeling agriculture and land use in an integrated assessment framework. *Climatic Change*, 56: 185-210.

- Schoneveld, G.C. (2010) *Potential land use competition from first-generation biofuel expansion in developing countries*. Occasional paper 58. CIFOR, Bogor, Indonesia.
- Searchinger, T., Heimlich, R., Houghton, R. a, Dong, F., Elobeid, A., Fabiosa, J., et al. (2008). Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science (New York, N.Y.)*, 319(5867), 1238-40. doi: 10.1126/science.1151861.
- Sheil, D., Casson, A., Meijaard, E., van Noordwijk, M. Gaskell, J., Sunderland-Groves, J., Wertz, K. and M. Kanninen (2009) *The impacts and opportunities of oil palm in Southeast Asia: What do we know and what do we need to know?* Occasional paper no. 51. CIFOR, Bogor, Indonesia.
- Sohngen, B., Tenny, C., Hnytko, M. and K. Meeusen (2009) Global forestry data for the economic modeling of land use. Chapter 3, *Economic Analysis of Land Use in Global Climate Change Policy*, Hertel, T. W., Rose, S. and R. S. J. Tol (Eds.) Routledge Explorations in Environmental Economics. Routledge: United Kingdom.
- Swarna Natha, H. and C. Tisdell (2009) The orangutan–oil palm conflict: economic constraints and opportunities for conservation. *Biological Conservation*. 18: 487-502.
- USEPA (2005) *Greenhouse gas mitigation potential in US forestry and agriculture*. EPA-R-05-006. Washington, D.C. US Environmental Protection Agency, Office of Atmospheric Programs.
- Valdes, A. and W. Foster (2010) Reflections on the role of agriculture in pro-poor growth. *World Development*, 38 (10), 1362 – 1374.
- Villoria, N. (2011) *Impacts of agricultural research-led productivity on land-use change*. Report prepared for the CGIAR Independent Science & Partnership Council's Standing Panel on Impact Assessment (SPIA).
- West, P. C., Gibbs, Holly K, Monfreda, C., Wagner, J., Barford, C. C., Carpenter, S. R., et al. (2010). Special Feature: Trading carbon for food: Global comparison of carbon stocks vs. crop yields on agricultural land. *Proceedings of the National Academy of Sciences of the United States of America*, 1-4. doi: 10.1073/pnas.1011078107.
- World Bank (2010) *World Development Report 2010: Development and Climate Change*. The World Bank: Washington, D.C.
- WWF-Indonesia (2008) *Deforestation, forest degradation, biodiversity loss and CO₂ emissions in Riau, Sumatra, Indonesia*. WWF Indonesia Technical Report: Jakarta, Indonesia.

Annexes

1. Full tables from Villoria (2011)

1.1 Crop germplasm improvement contributions to yield growth (1965 – 2004)

Annual percentage contribution of crop germplasm improvement to total factor productivity (TFP) growth (Source: Evenson, 2003, table 22.9, p.466-467).

Crop	Regions	Crop germplasm
All crops	All regions	0.72
	Asia	0.88
	Latin America	0.66
	MENA	0.69
	SS Africa	0.28
Barley	MENA	0.49
Beans	All regions	0.21
	Latin America	0.22
	SS Africa	0.18
Cassava	All regions	0.22
	Asia	0.17
	Latin America	0.10
	SS Africa	0.25
Lentils	MENA	0.28
Maize	All regions	0.66
	Asia	0.96
	Latin America	0.62
	SS Africa	0.22
Millets	All regions	0.56
	Asia	1.04
	SS Africa	0.74
Potatoes	All regions	0.81
	Asia	0.82
	Latin America	0.75
	SS Africa	0.74
Rice	All regions	0.79
	Asia	0.87
	Latin America	0.82
	SS Africa	0.54
Sorghum	All regions	0.50
	Asia	0.85
	SS Africa	0.30
Wheat	All regions	0.96
	Asia	1.01
	Latin America	1.06
	MENA	0.83
	SS Africa	0.53

1.2 Evenson and Rosegrant (2003) shocks aggregated to GTAP categories (percentages)

Category	Region	Lower-bound shock	Upper-bound shock
Vegetables and Fruits	Asia	-2.30	-2.99
	Latin America	-2.74	-3.56
	Middle East and North Africa	-0.13	-0.17
	Sub-Saharan Africa	-3.01	-3.91
Coarse Grains	Asia	-43.34	-56.34
	Latin America	-23.44	-30.48
	Middle East and North Africa	-11.41	-14.83
	Sub-Saharan Africa	-9.23	-12.01

These shocks come from adjusting the shocks for cassava, potatoes and lentils from 1.1 by their value shares in the aggregated GTAP category vegetables and fruits (top four rows) and likewise, sorghum, barley and maize are adjusted by their value shares on the GTAP category “Coarse grains”.

1.3 Decomposition of production changes in yield and area changes – developing and developed countries

Region	Variable	Wheat	Rice	Coarse Grains	Veg. and Fruits	Evenson and Rosegrant - All	Oilseeds	Other agric.	All Crops
Developing	Production	-43, -	-14, -	-6, -6	-4, -7	-10, -15	-7 -11	-3, -5	-8, -12
	Harv. Area	-5, -11	19, -	15, 25	-11, -	5, 7	-12, -16	-11, -	1, 1
	Yield	-38, -	-33, -	-21, -31	7, 8	-15, -22	4, 5	8, 10	-9, -13
	Exports	-85, -	19, -	-34, -38	-2, -1	-11, -7	3, 6	1, 6	-5, 0
	Imports	111, -	228, -	23, 50	6, 11	54, 99	-1, -2	6, 13	30, 56
Developed	Production	46, 76	53, -	9, 15	1, 1	16, 27	-1, -2	1, 1	12, 20
	Harv. Area	21, 30	24, -	-6, -8	-12, -	5, 8	-12, -18	-13, -	1, 2
	Yield	25, 46	29, -	14, 23	13, 20	11, 19	11, 16	14, 21	11, 19
	Exports	104, -	297, -	27, 49	4, 6	38, 65	-4, -7	4, 5	25, 43
	Imports	-2, 0	-6, -3	-1, -1	0, 0	0, 0	0, 0	0, 1	0, 1

Results reported here are percentage changes relative to the baseline year (2004) in production, harvested area, yields, exports and imports. The values are weighted averages using the following as weights: physical output in tons for production; hectares for area; and export and import values. For each scenario, lower and upper bounds are separated by a comma.

1.4 Comparison of results obtained by Villoria (2011) and Evenson and Rosegrant (2003)

	Variable	Wheat	Rice	Coarse Grains	Veg. and Fruits	Evenson and Rosegrant - All	Oilseeds	Other agric.	All Crops
Villoria (2011)	Price	28.9, 59.3	68.3, 135.1	20.2, 41.7	5.7, 9.8	13.4, 26.3	4.9, 8.5	5.22, 9.3	10.0, 19.3
	Production	6, 15	-10.6, -17.3	2.8, 6.6	-3.0, -5	-1.4, -1.1	-4.7, -7.2	-2.5, -3.8	-1.9, -2.3
	Harv. Area	9.4, 12.2	20.1, 26.8	8.0, 13.6	-10.6, -15.2	5.7, 8.3	-11.2, -16.1	-10.9, -15.0	1.5, 2.2
Evenson and Rosegrant (2003)	Price	29, 61	80, 124	23, 45		35, 66			
	Production	-9, -14	-11, -14	-9, -12		-8, -12			
	Harv. Area	3.5, 5.6	7.5, 9.4	1.1, 1.9		1.8, 4.6			

Results are percentage changes relative to the baseline year (2004) in prices, production and harvested area aggregated using as weights: output values for prices; physical output for production and area. For each scenario, the values for the lower and upper bounds are separated by a comma. The lower part of the table shows some of the results obtained by Evenson and Rosegrant (2003, table 23.3, p. 484). Omitted are changes for other grains, potatoes and root crops. Their results for maize are under the column coarse grains.

1.5 Changes in land covers – developing and developed countries

Region	Cropland	Forests	Pasture
Developing	0.92, 1.52	-0.53, -0.86	-0.39, -0.66
Developed	0.50, 0.87	-0.29, -0.51	-0.12, 0.36

These are productivity (rental share) weighted changes in land covers. The figures are weighted averages of all regions within the developing and developed countries using land rents as weights. For each scenario, values for lower and upper bounds are separated by a comma.

1.6 New hectares by crop and region (million hectares) under the counterfactual of no crop germplasm improvement since 1965

Region	Wheat	Rice	Coarse Grains	Veg. & Fruits	Evenson and Rosegrant - All	Oilseeds	Other agric.	All crops
Latin America	-4.65, -6.93	1.62, 2.3	4.83, 7.02	-0.52, -0.71	1.29, 1.68	0.48, 0.91	-0.59, -0.79	1.18, 1.8
S.E. Asia	-0.05, -0.06	6.98, 8.51	1.63, 2.52	-2.26, -2.84	6.3, 8.14	-3.32, -4.33	-1.86, -2.41	1.11, 1.4
Rest of Asia	5.26, 5.05	19.02, 24.91	19.64, 33.85	-17.01, -24.84	26.9, 38.96	-12.85, -18.6	-6.33, -8.97	7.72, 11.35
SS Africa	-0.42, -0.44	1.31, 1.77	2.5, 3.09	-0.96, -1.21	2.43, 3.2	-0.67, -0.87	0.08, 0.39	1.85, 2.72
MENA	-4.59, -7.97	0.42, 1.31	2.38, 3.84	1.0, 1.65	-0.79, -1.16	0.55, 0.98	0.35, 0.59	0.11, 0.41
Developed countries	24.91, 36.71	0.96, 1.56	-6.14, -8.1	-4.03, -6.31	15.7, 23.87	-7.56, -11.57	-2.16, -3.22	5.98, 9.07
All Regions	20.46, 26.36	30.31, 40.37	24.84, 42.22	-23.78, -34.25	51.83, 74.69	-23.37, -33.53	-10.51, -14.41	17.95, 26.75

1.7 Effects of declining productivity in Brazil's soybeans sector on production, yields, and area (percentage changes)

Region	Variable	Oilseeds	Wheat	Rice	Coarse Grains	Veg. & Fruits	Other Agric.
Brazil	Price	135	-2	-4	-3	-3	-3
	Harvested Area	-18	19	6	8	8	9
	Production	-67	13	-1	1	1	3
	Yield	-50	-7	-8	-7	-7	-6
	Exports	-95	18	50	8	10	20
Rest of the world	Price	2	0	0	1	0	0
	Harvested Area	6	-1	-1	-2	-1	-1
	Production	10	-0	-0	-0	-0	-0
	Yield	3	1	1	2	1	1
	Exports	33	-1	-2	-0	-0	-1

The values for the rest of the world are weighted averages using the following as weights: output values for prices, physical output in tons for area and yields, and export values for exports.

1.8 Effects of declining productivity in Brazil's soybeans sector on production and exports (all model regions and crops)

Region	Variable	Oilseeds	Wheat	Rice	Coarse Grains	Veg. and Fruits	Other Agric
Brazil	Production	-67	13	-1	1	1	3
	Exports	-95	18	50	8	10	20
Canada	Production	18	-2	-4	0	-0	-1
	Exports	25	-2	-10	-0	-1	-3
China	Production	8	0	-0	-0	-0	0
	Exports	29	2	1	0	0	-0
EU27	Production	21	0	0	-0	0	-0
	Exports	50	1	1	-0	0	-1
USA	Production	14	-1	-1	-0	-0	-1
	Exports	31	-2	-2	-1	-1	-4
Rest of the world	Production	6	0	-0	-0	0	-0
	Exports	34	-0	-2	-0	0	-1

All figures are percentage changes. Production and export value are weighted averages.

1.9 Changes in land cover in each Agro-ecological zone (AEZ) in Brazil (percentages)

AEZ	Cropland	Forests	Pasture
AEZ 1	-0.00	0.00	0.00
AEZ 2	-0.00	0.00	0.00
AEZ 3	-0.00	0.00	0.00
AEZ 4	-0.01	0.01	0.01
AEZ 5	-0.13	0.03	0.09
AEZ 6	-0.05	0.04	0.01
AEZ 10	0.00	0.00	-0.00
AEZ 11	-0.00	0.00	0.00
AEZ 12	-0.05	0.02	0.03

The table shows rental share weighted percentage changes in land cover by AEZ

1.10 Land rents per cover types and for oilseeds in each AEZ in Brazil (millions of USD\$)

AEZ	Oilseeds	Cropland	Forests	Pastures
AEZ 1	0	0	0	0
AEZ 2	3	21	0	6
AEZ 3	4	78	0	21
AEZ 4	71	301	26	62
AEZ 5	489	1484	123	555
AEZ 6	146	1321	272	204
AEZ 10	0	8	0	1
AEZ 11	0	0	0	0
AEZ 12	445	1727	67	153

1.11 New hectares by country after decline in productivity of Brazilian soybeans (million ha)

Region	Oilseeds	All other crops	All crops
Brazil	-3.9	3.6	-0.3
Canada	0.9	-0.5	0.4
China	1.4	-1.3	0.1
EU27	2.0	-1.8	0.1
Indonesia	0.3	-0.3	0.0
USA	2.6	-2.3	0.3
Rest of the world	5.3	-4.7	0.6
All regions	8.6	-7.4	1.2

1.12 Effects of increasing productivity in the oil palm sectors of Indonesia and Malaysia on production, yields and area (percentages)

Region	Variable	Oilseeds	Veg. oils and fats
Indonesia-Malaysia	Price	-26	-17
	Harvested area	10	
	Production	68	74
	Yield	58	
	Exports	197	98
Rest of the world	Price	-1	-1
	Harvested area	-2	
	Production	-3	-9
	Yield	-1	
	Exports	-3	-18

Values for the rest of the world are weighted using the following as weights: output values for prices, physical output (tons) for area and yields and export values for exports.

1.13 New hectares by country after increase in productivity of Indonesia-Malaysia oilseeds (million ha)

Region	Oilseeds	All other crops	All crops
Brazil	-0.7	0.6	-0.1
Canada	-0.2	0.1	-0.1
China	-0.3	0.3	0.0
EU27	-0.2	0.2	-0.0
Indonesia	1.1	-1.0	0.1
USA	-0.6	0.5	-0.1
Rest of the world	-2.9	2.6	-0.4
All regions	-3.8	3.3	-0.5

1.14 Change in land covers in Indonesia-Malaysia and the rest of the world (percentage changes)

Region	Cropland	Forests	Pasture
Indonesia-Malaysia	0.24	-0.24	0.00
Rest of the world	-0.02	0.01	0.01

Productivity (rental share) weighted changes in land covers. The figures for the rest of the world are land rent weighted averages of all regions except Indonesia-Malaysia.

2. Future land use projections

Projections by FAO suggest that, until 2030, an additional 47 M ha of land will be brought into production globally, a decrease of 27 M ha in developed and transition economies and an increase of 74 M ha in developing countries. As cropping intensity is projected to increase as well, harvested area will expand even faster, by 92 M ha, nearly all in developing countries where an annual expansion of 3 M ha is predicted. Disaggregating these across regions also illustrates that, while the rate of expansion will be slower than in 1990-2005, it will continue to be important factor in Sub-Saharan Africa and Latin America where area under crops is expected to increase by 39 and 31 M ha, respectively. These projections assume yield growth of 0.9% per year in line with recent experience. Importantly they do not consider land use for biofuels and forest plantations.

While these factors only extrapolate linearly, CGE models allow for adjustments to price and trade which induce supply response in regions where land is relatively abundant. Doing so increases the magnitude of estimates, highlighting the conservative nature of the FAO estimates even for food and feed only. Compared to the 1.8 M ha per year expansion predicted by FAO, other studies obtain much larger estimates of future land conversion for use by food commodities with annual values that range from 4.5 M ha {Fischer 2009} to 10 M (Al Riffai *et al.* 2010) or even 12 M ha (Eickhout *et al.* 2009). These estimates include the impacts for biofuels that are not considered in the FAO projections. The impact of biofuels on land conversion depends not only on availability of second generation technology but also on how strictly mandates will be enforced in light of increased evidence of high economic and environmental cost of strategies for biofuel expansion. Depending on these, the expected amount of land converted to biofuels until 2030 ranges between 18 and 44 M ha (Fischer *et al.*, 2009), a figure similar to what is predicted by general equilibrium models.

Although it has been one of the land use categories with the fastest expansion over the past decades, none of the existing studies include plantation forestry. Doing so would be desirable as plantation forests are planted on marginal land some of which are not suited to crop production, and may compete for pastureland. Estimated growth of this land use category, between 42 and 84 M ha in total (the latter based on continuation of past trends), can add significantly to total land demand (Carle and Holmgren 2008). Unlike the other commodities, most of the area increase occurs in Asia and in developed and transition countries where agricultural area is projected to decline.

After accounting for projected yield growth, FAO projections for food crops are slightly below historical trends. By contrast, CGE-based models predict land use changes that can be an order of magnitude larger above this figure. Adding biofuels adds roughly 1-2 M ha/yr. Plantation forestry could add some 1.5 M ha per year, though part of the required land does not compete with crop uses. A conservative projection is that 6 M ha additional land will be brought into production annually up to 2030. This would imply a total land expansion of land area between 120 and 240 M ha to 2030. As land use in developed and transition countries is in long-term decline and more of agricultural activity shifts to developing countries, projected land use changes in the latter are higher. Moreover, some two thirds of the land expansion in developing countries will be in sub-Saharan Africa and Latin America, the two regions in the developing world where land is still relatively abundant.

3. Appendix to section 2.3 “Formalizing the two competing perspectives into a single analytical framework”

The analytical framework developed by Hertel (2010) allows highlighting the conditions under which agricultural technologies are likely to result on land savings or land expansion. The framework is a partial-equilibrium model of a profit-maximizing farm sector operating under constant returns to scale. For convenience, the model is summarized in table 1A; the discussion here is succinct, so the reader is advised to read the original piece for the full discussion.

The model is expressed in terms of *percentage changes* in prices (p) and quantities (q); thus, equation 1A in table 1A is the demand schedule faced by agricultural producers where q_A^D is the percentage change in long run demand for agricultural output given a percentage change in agricultural output prices, p_A , ε_D is the elasticity of demand, and Δ_A^D is an exogenous demand shifter, e.g., population growth.

Table 1A. A simple model of long run and supply for agricultural land

$q_A = -\varepsilon_D p_A + \Delta_A^D$	(1A)	Demand for agricultural products
$q_L^D = q_A^S - \sigma(p_L - p_A) - \Delta_L^D$	(2A)	Derived demand for land
$p_A = \sum_j \theta_j p_j$	(3A)	Zero profits condition
$q_L^S = v_L p_L - \Delta_L^S$	(4A)	Land supply

Source: Hertel (2010)

Hertel postulates a global production function that combines land with variable inputs, the latter assumed to be in perfectly elastic supply in the long-run. Assuming constant returns to scale, and zero pure economic profits, the percentage change in global derived demand for land (equation 2A in table 1A), q_L^D , is a function of total output expansion (q_A^S), changes in the price of land (p_L) relative to output price (p_A), and the elasticity of substitution between land and non-land inputs, σ , which captures the potential to increase yields when land returns increase.

Equation 3A in table 1A is the zero profit condition whereby the percentage change in output price is the cost-share (θ_j , where j indexes inputs) weighted sum of changes in inputs prices (p_j). The assumption of perfectly elastic supply of all the non-land inputs implies that their prices are unchanged in the long-run, i.e., $p_j = 0$ for all $j \neq$ land, and thus, (3) becomes:

$$p_A = \theta_L p_L \quad (5A)$$

As in the case of output demand, Hertel attaches an exogenous shifter, Δ_L^D to equation 2A that captures the possibility of having exogenous yield growth. As noted by the author, this is a very important simplification as yield growth is likely to be endogenously determined and responsive to price incentives; however, this simple representation of yield growth provides a convenient vehicle to understand the effects of various economic and technological forces on the land use effects of technical progress.

Finally, equation 4A closes the model by describing the percentage change in land supply to the agricultural sector, q_L^S , as a function of the land supply elasticity, v , and land prices, p_L . As before, this equation has an exogenous shifter of land supply associated with other uses determined outside the agricultural sector.

In this review we focus on the effects of technical progress on land use, Δ_L^D ; thus we set $\Delta_A^D = \Delta_L^S = 0$. To understand the how the different economic forces captured by the elasticities interact with an exogenous boost to yields in shaping land use, we can use (1) to eliminate agricultural output from (2), by recognizing that in equilibrium, $q_A^D = q_A^S$. Further simplification is achieved by using (5A) to eliminate output price, p_A . Formally:

$$q_L^D = -\varepsilon_D \theta_L p_L - \sigma(p_L - \theta_L p_L) - \Delta_L^D. \quad (6A)$$

The long run equilibrium implies that land markets are in equilibrium, thus we can combine (4A) and (6A) to solve for land prices:

$$p_L = \frac{-\Delta_L^D}{v + \varepsilon_D \theta_L + \sigma(1 - \theta_L)} \quad (7A)$$

This is equation 11 in the text.