Modeling Land Intensification Response in GTAP: Implications for Biofuels Induced Land Use Change

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Abstract

Proper modeling of land intensification response is critical since it affects, for example, in response to a rise in crop prices driven by biofuels expansion, how land use change in a region may be biased towards the intensive margin as opposed to the extensive margin, and consequently how much greenhouse gas would be emitted. In this paper, we model land intensification characterized by the cropping intensity response to price changes and estimate the response parameter at the global level. We run a modified GTAP-BIO to demonstrate that introduction of this response mechanism would significantly revise the projections of induced land use change. Sensitivity analyses are also conducted for the estimated response parameter to examine the ballpark of relevant land use change variables.

1. Introduction

Biofuels expansion can cause indirect land use change since biofuels feedstock such as corn, oil crops, and sugar crops, needs land to produce. In response to increased demand for biofuels feedstock, farmers may raise crop productions through using more land, i.e., the cropland to be converted from other types of land such as forest and pasture (land extensification), and/or through more intensive use of the existing land such as using more fertilizer to increase yield or enhancing cropping intensity via multiple cropping or cropping on fallow land (land intensification). Since using more land may increase greenhouse gas emissions due to relatively richer carbon contents in forest and pasture while using the existing cropland does not, to what extent biofuels expansion can be justified is thus determined by the induced land use change at the relative margin – the intensive margin relative to the extensive margin. As such, it is crucial for economic models to capture the extensification and intensification responses of land use properly, which has long been positioned among the most controversial topics in economic research.

Earlier studies on biofuels induced land use change that did not employ an economics framework (e.g. Fargione et al., 2008; Tilman et al., 2006) or those equipped with the economic mechanism but assumed away land intensification responses (e.g. Searchinger et al., 2008) tend to significantly overestimate the induced land use change. In contrast, several studies (e.g. Broch et al., 2013; Dumortier et al., 2011; Hertel, Golub, et al., 2010; Keeney & Hertel, 2009) introduced intensification response in their models and this led to significant reductions in the estimated land use change. The intensification response in these studies though, was limited to crop yield response, with the response in cropping intensity still remaining untouched.[1]

Changes in cropping intensity in the world have been particularly evident since mid-2000s. Data from Food and Agricultural Organization of the United Nations (FAO) show that increases in harvested area have significantly outpaced increases in cultivated area in many countries around the world, leading to the rapid rise in world cropping intensity over this period (Figure 1). [2] While this emerging land use change pattern has received some discussions (e.g. Babcock & Iqbal, 2014; Siebert et al., 2010), incorporating this pattern into a model was attempted only recently by Taheripour et al. (2016) using GTAP-BIO - an extended version of the standard GTAP model with explicit modeling of biofuels and land use change.

In the earlier versions of GTAP-BIO, land use change in terms of the relative movement between harvested area and cropland cover was treated in a relatively simple way, where the changes in harvested area were simply equated to the changes in cropland cover.[3] This simplified treatment essentially assumed away the possible changes in cropping intensity and thus led to studies using this model including Keeney and Hertel (2009), while being capable of capturing land intensification response through crop yield, still overestimate the induced land use change due simply to the lack of a mechanism to capture the response in cropping intensity.

Taking into account historical observations on worldwide rises in cropping intensity, Taheripour et al. (2016) updated GTAP-BIO with a mechanism that allows for changes in harvested area to depart from changes in cropland cover. Instead of equating the changes in harvested area and cropland cover as in earlier GTAP-BIO, this updated version expresses the change in cropland cover in a region as a ratio of the change in harvested area in that region, and these regional ratios were derived by taking the average changes in harvested area and cropland cover observed over the 2003-2013 period. However, as fixed parameters in the model, these ratios are not allowed to change or respond to price changes as their crop yield counterparts do. To some extent, these fixed ratios have also ignored the fact that the corresponding historical ratios have been changing over time. More importantly, the derivation of these ratios *per se* did not isolate potentially different drivers of the changes in cropping intensity, for example, the changes in cropping intensity driven by changes in crop price or the changes in cropping intensity that simply follow their own trends. Therefore, the introduced land use change ratio might have mixed up cropping intensity changes due to biofuels expansion that work through the price channel with cropping intensity changes due to other factors.

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[1] Cropping intensity is defined as a ratio – harvested area divided by cultivated area. This ratio is also referred to as multiple cropping index in some publications, for example, OECD-FAO (2009). The difference between the two land area concepts – harvested area and cultivated area, is straightforward: if a crop is planted and harvested twice on the same piece of land in the same year, the harvested area will double the cultivated area.

[2] We use the arable land and permanent crops data from FAO as the proxy for cultivated area.

[3] The concept of cropland cover used in GTAP is largely comparable to cultivated area used for the FAO data.

Upon reviewing the previous efforts, the bottom line can be drawn that correlation between cropping intensity change and the policy-driven biofuels expansion needs to be proven in the first place and if there is such a correlation, the biofuels-driven part of the cropping intensity change needs to effectively isolated. If, for instance, we can establish a linkage between biofuels expansion and cropping intensity via crop prices, and this linkage can be substantiated with economic theory and/or empirical evidence, then the following simulations will generate results convincingly grounded. This is also the very motivation of our present research.

Fortunately, numerous studies have provided the economics rationale or empirical evidence that the biofuels boom over the past more than a decade has contributed to the rise of crop prices, though the estimated contributions vary across studies (e.g. Babcock, 2012; Beckman et al., 2011; de Gorter & Just, 2009; Gohin & Tréguer, 2010; Hertel & Beckman, 2011; Hertel, Tyner, et al., 2010; Hochman et al., 2010; McPhail & Babcock, 2008; Taheripour et al., 2011; Tyner & Taheripour, 2008; Wu & Langpap, 2015). So the first part of this linkage - the relationship between biofuels expansion and crop prices, can be established. On the other hand, the FAO data also show that the world cropping intensity moved largely in line with the world crop prices for most years over the 1991-2013 period, signaling a potentially high correlation between the two (Figure 2). This to-be-substantiated second part of the linkage will be the focus of the present paper.

In contrast with the fixed ratio approach to the cropping intensity modeling as used by Taheripour et al. (2016), we introduce in GTAP-BIO a variable that defines the change in cropping intensity. This variable will be determined endogenously offering the flexibility for the multiple cropping based land intensification to respond to price changes. To what extent this variable responds to a change in price is governed by an intensification response parameter, which will be derived mathematically and estimated econometrically. Since the estimation was based on a structural equation derived mathematically, the consistency between the estimated parameter and the parameter indicated in theory has thus been maintained, and this leads smoothly to the following calibration in the model.

Throughout the formulation and calibration procedure, this paper highlights the close relationship between the introduced cropping intensity response and the existing crop yield response in the model. In the standard GTAP model and its variants, the crop yield response with respect to price changes is governed by a parameter drawn from several earlier studies that estimated yield responses econometrically. The limitation of these estimations though, lies in the data used since they were all based on harvested area. This implies that the estimated yield response, while having captured the yield response per unit of harvested area, failed to capture the full picture of land intensification response – the yield response per unit of cultivated area (the physical land). The gap left between the two types of yield response, as this paper shows, can be filled naturally by the introduced cropping intensity response.

The rest of this paper is structured as follows. Section 2 formulates cropping intensity response and its relationship with crop yield response and derives the structural equation to be estimated econometrically. Section 3 presents the data, estimation strategy, and estimation results. Section 4 uses the estimated parameter to calibrate and modify the existing model. In section 5, simulations are undertaken to compare different studies and highlight the feature of the newly introduced cropping intensity response. Section 6 concludes.

2. Formulation of Cropping Intensity Response

Let us start with an identity to describe the relationship between harvested area, cultivated area, and cropping intensity, as shown in equation (1) where *Q* denotes quantities while superscripts *H*, *C*, and *I* denote harvested area, cultivated area, and cropping intensity, respectively. If we define cropping intensity, Q^I, as harvested area, Q^H, divided by cultivated area, Q^C, then (1) shows that harvested area is simply cultivated area multiplied by cropping intensity. For simplicity, we ignore the regional index for now which will be added later on. In the form of percentage change where capital letter *Q* is replaced by its lower case, equation (2) shows that the percentage change in cropping intensity may be expressed as an area-change gap - the difference between the percentage changes in harvested area and cultivated area.

(1) $$Q^H \equiv Q^C \frac{Q^H}{Q^C} \equiv Q^C Q^I$$

(2) $$q^H = q^C + q^I$$

If there is no change in cropping intensity, that is, $q^I = 0$, then the percent change in harvested area simply follows the percent change in cropland cover. This is in contrast with the equation build into the earlier versions of GTAP-BIO where the absolute change in cropland cover was equated to the absolute change in harvested area, that is, $Q^C q^C = Q^H q^H$ (Birur et al., 2008; Keeney & Hertel, 2009) or the generalized version of the equation where the absolute change in cropland cover was proportionate to the absolute change in harvested area, i.e. $Q^C q^C = \gamma Q^H q^H$ (Taheripour et al., 2016).

We now proceed to explore how cropping intensity is associated with crop yield, a concept which we may first consider as a broad measure of crop output per unit of land area. The relationship between crop yield, crop output, and land area can thus be given by

(3) $$q^O = q^L + y$$

where q^O, q^L, and y denote the percentage change in crop output, land area, and crop yield, respectively.

Land area allocated to produce a crop may be measured either by harvested area or by cultivated area. Given a particular land area metric, a corresponding yield rate would apply. Thus, the two different land area metrics – harvested area and cultivated area, need to be associated with different yield rates, as shown in (4) through (6) where the superscripts *H* and *C* denote land units measured by harvested area and cultivated area, respectively.

(4) $q^O = q^H + y^H$
(5) $q^O = q^C + y^C$
(6) $y^C - y^H = q^H - q^C = q^I$

It should be noted that while crop yield is conventionally defined as crop output per unit of harvested area, as shown in (4), we now introduce a comparable crop yield concept in (5) as this would lead to a meaningful expression of cropping intensity in (6) which implies that a change in cropping intensity, while being expressed as an area-change gap as in (2), may also be expressed as a yield-change gap – the difference between the percentage change in crop yields measured respectively by cultivated area and harvested area.

Now we turn to the relationship between cropping intensity and crop price. In the CES form, input demand for land in the farming sector may be given by

(7) $q^L = q^O - a^L - \sigma(p^L - p^O - a^L)$

where q^L and q^O are percentage changes in land area and crop output, respectively; p^L and p^O are percentage changes in land price and crop price, respectively; a^L denotes the percentage change in land productivity; and σ is the elasticity of substitution among inputs. Again, we use a broad land area concept at this stage and do not distinguish between harvested area and cultivated area.

Rearranging land demand equation (7), we have

(8) $q^O - q^L = a^L + \sigma(p^L - p^O - a^L)$

The left hand side of (8) is output change net of land use change, i.e., the yield change. If we assume that non-land factor prices are determined outside the farming sector so land remains as the only quasi-fixed factor – the long-run case in (Keeney & Hertel, 2009), the change in crop prices may be expressed as the change in land price weighted by the share of land cost in total crop production costs, denoted by S^L.

(9) $p^O = S^L p^L$

Inserting (3) and (9) into (8) yields

(10) $y = (1-\sigma)a^O + \sigma \frac{(1-S^L)}{S^L} p^O$

Note that a general restriction for the Allen-Uzawa elasticity of substitution (AUES) requires

(11) $\sum_j S_j \sigma_{ij} = 0$

where S_j denotes the share of input *j* in the total cost. Therefore, in the CES form with identical elasticities of substitution across the off-diagonal components in the AUES matrix, we have

(12) $\sigma^{LL} = -\frac{(1-S^L)\sigma}{S^L}$

where σ^{LL} is the own elasticity of substitution of land. With (12), we can further simplify (10) into

(13) $y = (1-\sigma)a^O - \sigma^{LL}p^O$

(13) decomposes crop yield change into two components. The first is the productivity term which may include a yield trend or yield affected by climate conditions. In the second component, the own AUES of land, σ^{LL}, essentially captures the crop yield response with respect to the change in crop price. This response mechanism was also adopted by Keeney and Hertel (2009).

Recall that land area may be measured by harvested area or cultivated area, as shown in equations (4) through (6). Likewise, we can rewrite equation (13) into two separate equations:

(14) $y^H = (1-\sigma^H)a^H - \sigma^{HH}p^O$
(15) $y^C = (1-\sigma^C)a^C - \sigma^{CC}p^O$

The two equations state that in response to a change in crop price, the change in crop yield may have two different metrics, based respectively on harvested area and cultivated area. The two different yield metrics are thus reflected by two different response parameters σ^{HH} and σ^{CC}, and the corresponding two different elasticities of substitution.

Since the change in cropping intensity may also be expressed as a yield change gap in (6), the difference between equations (14) and (15) leads to

(16) $q^I = (1-\sigma^C)a^C - (1-\sigma^H)a^H - (\sigma^{CC} - \sigma^{HH})p^O$

where the change in cropping intensity q^I is decomposed into two components: the productivity term $(1-\sigma^C)a^C - (1-\sigma^H)a^H$ that describes a cropping intensity trend and cropping intensity change due to changing climate conditions; and the price response component where the gap between the two own AUES of land, $\sigma^{CC} - \sigma^{HH}$, defines the cropping intensity response with respect to the change in crop price. (16) is the structural equation to be estimated econometrically and the estimated parameter $\sigma^{CC} - \sigma^{HH}$ will be used in the following calibration of the model.

3. Data and Estimation

We use global level annual data, ranging from 1991 to 2013, to estimate equation (16). The land use and crops data including harvested area, arable land and permanent crops, crop productions and crop gross production values are collected from FAO. Crop data cover all FAO-defined primary crops. Crop prices are calculated from crop productions and gross crop production values (in current US dollar). Climate data are global annual mean temperature observations collected from IPCC Data Distribution Centre.

Based on the structural equation (16), we construct the estimation question as

$$(17) \quad q_t = \beta_0 + \beta_1 W_t + \beta_2 p_t + \beta_3 p_{t-1} + u_t$$

where q_t is the percentage change in cropping intensity; the constant term β_0 captures the growth trend of cropping intensity; W_t is the absolute change in global mean temperature; p_t and p_{t-1} are the aggregate percentage change in crop prices at year *t* and the last year *t*-1, respectively; u_t is the error term. Clearly, (17) echoes (16) with the productivity term $(1-\sigma^C)a^C - (1-\sigma^H)a^H$ in (16) being represented jointly by a trend term and a temperature term in (17). The effects of crop price are also considered from two consecutive years – current year and last year, in order to take into account the possibly delayed statistics of cropping intensity as crops may be planted and harvested in different years.

Consistent with the structural equation, (17) will isolate the cropping intensity change driven by price changes since the estimated response parameter β_2 and β_3 will only capture the price-mediated cropping intensity responses.

Since the equation to be estimated is a structural equation containing endogenous variables- crop prices, at the right hand side of the equation, and land prices do not enter this estimation equation due to the assumption made in (9), this raises the issue of endogeneity in which case OLS estimates would be inconsistent. To overcome this issue, we use the Instrumental Variable approach (IV) to estimate (17). The instrumental variables used in the estimation are world seafood prices, which were also collected from FAO. The idea of using this IV is that world seafood prices are highly correlated with crop prices since both of them are food (strong first stage) but are not correlated directly with cropping intensity or land prices since seafood does not need land to produce and land use decisions that affect changes in cropping intensity are not dependent on seafood prices (exclusion restriction).

Table 1: Estimation results for cropping intensity response

	Crop Price	Crop Price, Lagged	Temperature	Trend
OLS	0.0633***	0.0126	-1.3030	0.3903*
	(0.0178)	(0.0176)	(0.9867)	(0.1885)
IV	0.0836**	-0.0212	-1.2355	0.4426*
	(0.0310)	(0.0282)	(1.1298)	(0.2236)

Note: Standard errors are in parentheses; *, ** and *** denote significance at 10%, 5%, and 1% levels, respectively. Estimated coefficients respectively indicate per cent changes in cropping intensity in response to one per cent increase in crop prices and one degree Celsius increase in temperature, and a constant per cent change in cropping intensity per annum.

Table 1 presents the estimated results from both OLS and IV estimations. As Table 1 shows, global cropping intensity responded significantly to the change in crop prices, particularly the change in crop price of the current year. The IV estimation indicates that 1 percent increase in global crop price would raise cropping intensity by some 0.08 percent in the current year. However, 1 percent increase in global crop price was estimated to reduce cropping intensity by some 0.02 percent in the next year, though this estimate was insignificant. The sum of these two numbers, 0.06, representative of the overall global cropping intensity response, will be used in the following model calibration and simulations.[4] Moreover, global cropping intensity appears to have a moderate trend and its response to global temperature appears to be insignificant.

4. Calibration and Modification in GTAP-BIO

As indicated in (7), cropping intensity response would be affected by land price while it has been assumed away via (9). In GTAP-BIO, however, land value data is available for the base year. This would enable us, as the following calibration shows, to take advantage of this available information so as to implement the full equation (7) which takes land price into account.

(4) and (5) have shown that land area may be measured by harvested area or cultivated area. Following the same vein, we can rewrite (7) as

$$(18)\quad q^H = q^O - a^H - \sigma^H(p^H - p^O - a^H)$$
$$(19)\quad q^C = q^O - a^C - \sigma^C(p^C - p^O - a^C)$$

where superscripts *H* and *C* distinguishes variables and parameters applied respectively to harvested area and cultivated area. The differentiated σ^H and σ^C describe two different elasticities of substitution, when viewed from the perspective of harvested area versus from the perspective of cultivated area, for a given change in the relative price– the price of land relative to the price of crops. The gap between the two equations determines the percentage change in cropping intensity.

$$(20)\quad q^I = \frac{a^I + \sigma^I(p^H - p^O)}{1 - \sigma^I - \sigma^H}$$

where $a^I \equiv (1-\sigma^C)a^C - (1-\sigma^H)a^H$ and $\sigma^I \equiv \sigma^C - \sigma^H$. If we ignore the difference between land prices expressed in harvested area and land prices expressed in cultivated area, that is, if we assume $p^H = p^C = p^L$, (20) will collapse into

$$(21)\quad q^I = a^I + \sigma^I(p^L - p^O)$$

Indeed, the simplified (21) offers a more straightforward way of understanding the determination of cropping intensity and its close relationship with crop yield. It shows that the

[4] The implemented parameter value was round off to four decimal places, i.e. 0.0625.

cropping intensity response with respect to a change in the relative price captured by σ^I, is expressed in the form of elasticity of substitution which is essentially a gap between the elasticity of substitution based on cultivated area and the elasticity of substitution based on harvested area. Notably, this formulation of cropping intensity is very similar to how crop yield is formulated in (8). Both the elasticity of substitution σ in (8) and the elasticity of substitution gap σ^Iin (21) have a positive sign in front of them, indicating that they both respond positively to a rise in the price of land relative to the price of crops.

If we define $\sigma^{II} \equiv \sigma^{CC} - \sigma^{HH}$, the cropping intensity response parameter that has been estimated in (16), then the cross AUES σ^Ican be related to its own AUES counterpart σ^{II} via (12). That is, the substitution elasticity gap in (20) may be calibrated using the estimated cropping intensity response parameter and land cost share, and this procedure, again, highlights the connection between cropping intensity and crop yield as their responses to crop price are calibrated in a very similar way.

With this calibration, (20) becomes

$$(22) \quad q^I = \frac{(1-S^L)a^I - S^L\sigma^{II}(p^H - p^O)}{1 - S^L(1 - \sigma^{II} - \sigma^{HH})}$$

In the latest version of GTAP-BIO, the yield response parameter, σ^{HH}, has been calibrated for individual regions and land cost shares are also available at the regional level. This allows us to implement (22) in GTAP-BIO as

$$(23) \quad q_r^I = \frac{(1-S_r^L)a_r^I - S_r^L\sigma^{II}(p_r^H - p_r^O)}{1 - S_r^L(1 - \sigma^{II} - \sigma_r^{HH})}$$

where *r* is the index of regions; p_r^H and p_r^O are regional price index for cropland and crops, respectively; while a^Ihas been estimated at the global level, a_r^I is a to-be-shocked variable here, allowing each region to be identified with a distinctive cropping intensity trend.

In GTAP-BIO, total land supply is fixed for each Agro-Economic Zone (AEZ) in each region. This implies that, where land is converted across different types of land including forest, pasture, and cropland, land use change at this level must be measured in physical area in order to “compare apple with apple”. For cropland, its change thus needs to be measured in cultivated area at this level. However, where the total cropland is allocated across individual crops, the land area metric needs to be shifted to harvested area. This is because the same piece of cropland (measured in cultivated area) may be used for planting and harvesting different types of crops in a single year (the multiple cropping case), and as such, it would be misleading to measure individual crops in cultivated area. Also, as pointed out earlier, the crop yield response parameter, which governs the change in crop yield in the model through a calibration procedure, was also derived based on harvested area. Thus, it would be more reasonable to measure land use change in harvested area at the individual crop level.

In order to accommodate the measurement gap between harvested area and cultivated area at different land use levels, we bring in equation (2) and modify the existing land supply equation and the zero profit condition for individual crops as

(24) $q_{i,r}^{H} = q_{i,r}^{C} + q_{r}^{I}$
(25) $q_{i,j,r}^{H} = q_{i,r}^{C} + q_{r}^{I} - \sigma_{r}^{T}(p_{i,j,r}^{H} - p_{i,r}^{C} + q_{r}^{I})$
(26) $p_{i,r}^{C} = \sum_{j} S_{j,r} p_{i,j,r}^{H} + q_{r}^{I}$

where *i* and *j* represent each AEZ and crop sector, respectively; σ_{r}^{T} is the elasticity of land transformation calibrated for each region. q_{r}^{I}, the variable that defines the change in cropping intensity in a region, essentially works to convert between cultivated area and harvested area. It also works in (25) and (26) to adjust the relative price change to ensure that the land value in a region, whether measured in harvested area or cultivated area, should be the same.

5. **Simulation and Sensitivity Analysis**

In the simulations of GTAP-BIO with the above modified equations, we shock the US corn ethanol production from its 2004 level (3.4 billion gallons) up to 15 billion gallons, the mandated amount capped at 2015. Some of the key parameters governing land use change including the crop yield response parameter and the elasticities of land transformation between different land uses, are taken from several earlier studies so that the simulation results are comparable.

We began our experiments with the latest set of GTAP-BIO data used in Taheripour et al. (2016), where the yield response parameter has been calibrated for individual regions with these regional parameter values centering around 0.25 within the range [0.175, 0.325]. The elasticity of land transformation between major land uses including forest, pasture, and cropland has also been differentiated across regions, with a central value around -0.1. Given these land use parameter values, we first ran an experiment without cropping intensity response, i.e. $\sigma^{II} = 0$ in (23) to establish a reference case and then compare it to an experiment with cropping intensity response, $\sigma^{II} = 0.0625$. Table 1 shows that, without cropping intensity response, the expansions in global harvested area and cropland cover due to the expansion in US corn ethanol are about 0.9 million hectares (MHa) and 1.0 MHa, respectively. The relative size of these two numbers largely mirrors the relative size between harvested area and cropland cover in the base data. When cropping intensity response is introduced, global harvested area expansion increases to nearly 1.6 MHa while global cropland cover expansion falls to below 0.9 MHa.

Clearly, the introduced cropping intensity response creates a wedge effect, forcing the global expansion in harvested area to depart from and move above the global expansion in cropland cover. Apart from this wedge effect, cropping intensity response also triggers a productivity effect, leading to the average expansion in global harvested area and cropland cover with cropping intensity response higher than the average expansion without cropping intensity response. This productivity effect reveals that, if land is allowed to be multiple cropped, it effectively raises the productivity of cropland as more crops can be produced at the same cropland. Driven by higher profitability due to this improved productivity, more land from forest and/or pasture will be converted to cropland.

The wedge effect and productivity effect caused by cropping intensity response also exist across regions, with an exception for Sub-Saharan Africa where the expansion in harvested area is lower than the expansion in cropland cover. As indicated in (23), this idiosyncratic land use response in Sub-Saharan Africa may reflect the combined effect of a low land cost share and a small land price rise due to high land supply elasticity in this region. Despite this weak cropping intensity response, this group of experiments show that Sub-Saharan Africa leads the world in cropland cover expansion, followed by the United States, which however tops the world in harvested area expansion. Both regions are projected to experience major land use expansions following the ethanol demand shock.

As mentioned earlier, several versions of GTAP-BIO with different parameter values have been used in different studies. We would try different parameter values particularly the key parameter values that govern the model's land use responses in order to help understand how the introduced cropping intensity response mechanism works under different contexts and to some extent enable the comparison of studies using similar models.

Departing from the parameter values used in Taheripour et al. (2016), we would first try a uniform yield response parameter value, 0.25, across regions, a value that has been used in a number of earlier studies. With this uniform yield response, Table 2 shows an overall moderately higher land use expansions following the same shock while the cropping intensity response across regions, as gauged by the land use change ratio – the harvested area expansion divided by cropland cover expansion,[5] remains largely unchanged. This indicates that the regionally calibrated yield responses combine to be moderately higher than the uniform yield response.

Based on this uniform crop yield response, we now conduct the third group of experiments with a uniform elasticity of land transformation across regions and major land uses – forest, pasture, and cropland. This uniform value of -0.11 was used in Keeney and Hertel (2009) to simulate a 1 billion gallon increase in US corn ethanol. With this uniform land supply elasticity, Table 3 shows that while regions still respond heterogeneously in cropping intensity and land expansions, the overall land use expansions, whether measured in harvested area or cropland cover, are remarkably higher than the above two groups of experiments. Sub-Saharan Africa,

[5] As mentioned earlier, this ratio has been used as a parameter in Taheripour et al. (2016) to govern the relative change between harvested area and cropland cover. In this paper, however, this ratio may change in each region and can be linked to the percent change in cropping intensity defined in this paper with $\gamma = \frac{Q^L(q^H - q^I)}{Q^H q^H}$ where γ is the defined land use change ratio. For a particular region, an increase in cropping intensity q^I, the percentage change form of Q^I as defined in (1), leads to a decrease in land use change ratio γ.

the region leading the world's expansion in cropland cover in the above experiments, now is dwarfed by the United States which tops the world regions in both harvested area expansion and cropland cover expansion. This suggests that the regionally calibrated land supply elasticities have played a significant role in reducing the induced land use demands around the world and changing the land use distributions across regions.[6]

Notably, with this uniform land supply elasticity, global cropping intensity response also weakened. The gauged global land use change ratio increases from less than 0.6 in the above two groups of experiments to about 0.7 in the current experiment. The weakening in global cropping intensity response is quite intuitive since the overall higher land supply elasticity renders higher availability in cropland, meaning that the physical land is cheaper now so land will expand relatively more at the extensive margin than at the intensive margin. This weakening response in global cropping intensity also becomes more evident if we replace the uniform land supply elasticity, -0.11, with -0.2, the value used by Hertel, Golub, et al. (2010). As shown in Table 4, this weakening trend continues with the increased land supply elasticity. Due to the relatively faster expansion in cropland cover, the global land use change ratio now increases to 0.8 with regions showing similar trends and the United States remaining as the global leader in land use expansions.

Since the estimated cropping intensity response parameter is the focus of this paper and variations of this parameter value will undoubtedly affect the simulation results, just like the different land supply elasticities and yield response parameters discussed above, we have conducted systematic sensitivity analysis (SSA) for the estimated parameter. The SSA was undertaken via the Gaussian Quadrature approach, based on the assumption of triangular distribution of the parametric variations (DeVuyst & Preckel, 1997; Pearson & Arndt, 2000). The cropping intensity response parameter was judged to vary within the range [0, 0.125], that is, plus or minus 100% of the point estimate, approximating the 95% confidence interval of estimated cropping intensity response to the crop price of the current year. The variations in land use change, including harvested area and cropland cover, from this SSA are reported in Tables 5 and 6, respectively, where the 95% confidence interval were constructed on the assumption of normal distributions of these land use change variables.

As the tables show, how these land use change variables are affected by the parametric uncertainty depends on how far their mean values with cropping intensity response are away from their reference values assuming no cropping intensity response. The further the mean value of a land use change variable is away from its reference value, the more vulnerable is this variable to the variations of the parameter. Compared to cropland cover expansions, harvested

6 in Taheripour et al. (2016), the elasticities of land transformation for United States and Sub-Saharan African are -0.02 and -0.3, respectively, which are the average value of the elasticity of transformation between cropland and pasture and the elasticity of transformation between forest and the cropland-pasture bundle in the respective region. It should also be noted that while this value for the US, -0.02, is lower than the value used in Keeney and Hertel (2009), it is the same as the estimated value in Barr et al. (2011) for the 2004-2006 to 2007-2009 period.

area expansions with cropping intensity response are generally further away from its reference value, due to the above-mentioned productivity effect. For example, the global harvested area expansion under cropping intensity response is about 0.6 MHa greater than the expansion without cropping intensity response. This gap is much greater than its counterpart in the global cropland cover expansion, which is only 0.1 MHa lower than the reference value. As a result, the confidence interval for global harvested area expansion [1.1 MHa, 2.1Mha] is much wider than the confidence interval for the global cropland cover expansion [0.8 MHa, 1.0Mha]. This pattern also holds across regions. With cropping intensity response, regions experiencing larger expansions in harvested area tend to have wider confidence intervals for harvested area expansions, e.g. [0.2 MHa, 0.8MHa] for the United States, than regions with moderate harvested area expansions, e.g. [0.38 MHa, 0.42 MHa] for Sub-Saharan Africa.

6. **Conclusion**

We have formulated the cropping intensity response with respect to the change in crop prices and estimated the response parameter at the global level based on recent historical observations. We then calibrate an elasticity of substitution parameter using the estimated response parameter and the available information on land cost share. With modified GTAP-BIO, we ran several experiments to show how the introduced cropping intensity response mechanism affects land use change around the world and how this mechanism differs from previous studies.

The introduced cropping intensity response has immediate connections with the existing parameters governing land demand and supply in the model. This paper shows that cropping intensity response parameter and the existing yield response parameter come side by side and they jointly define the full yield response for a given piece of physical land. Also, the change in cropping intensity can be affected by the elasticity of land transformation across major land uses including forest, pasture, and cropland. An increase in this land supply elasticity would relieve the pressure of land demand and thus lessen the response of cropping intensity. With systematic sensitivity analysis, we show that variations in the cropping intensity response parameter would affect land use change differently across land uses (harvested area versus cropland cover) and across regions, as has been explained.

While the US ethanol expansion was used in this paper to exemplify how the introduction of cropping intensity response may affect the assessment of induced land use change, the built in response mechanism is rather general. Any shocks transmitted through crop prices will be mirrored at this type of intensive margin. If, for example, climate change is believed to be dampening crop yields causing crop prices to hike, the resulting cropping intensity response would imply the existing cropland to be used more efficiently and accordingly, crop productions may have a rebound, which to some extent helps alleviate the adverse effect of climate change by making agricultural productions more adaptive. Certainly, interesting stories like this need to be substantiated in future research and we expect the introduced cropping intensity response mechanism will open a door for future research in many relevant areas.

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Appendix

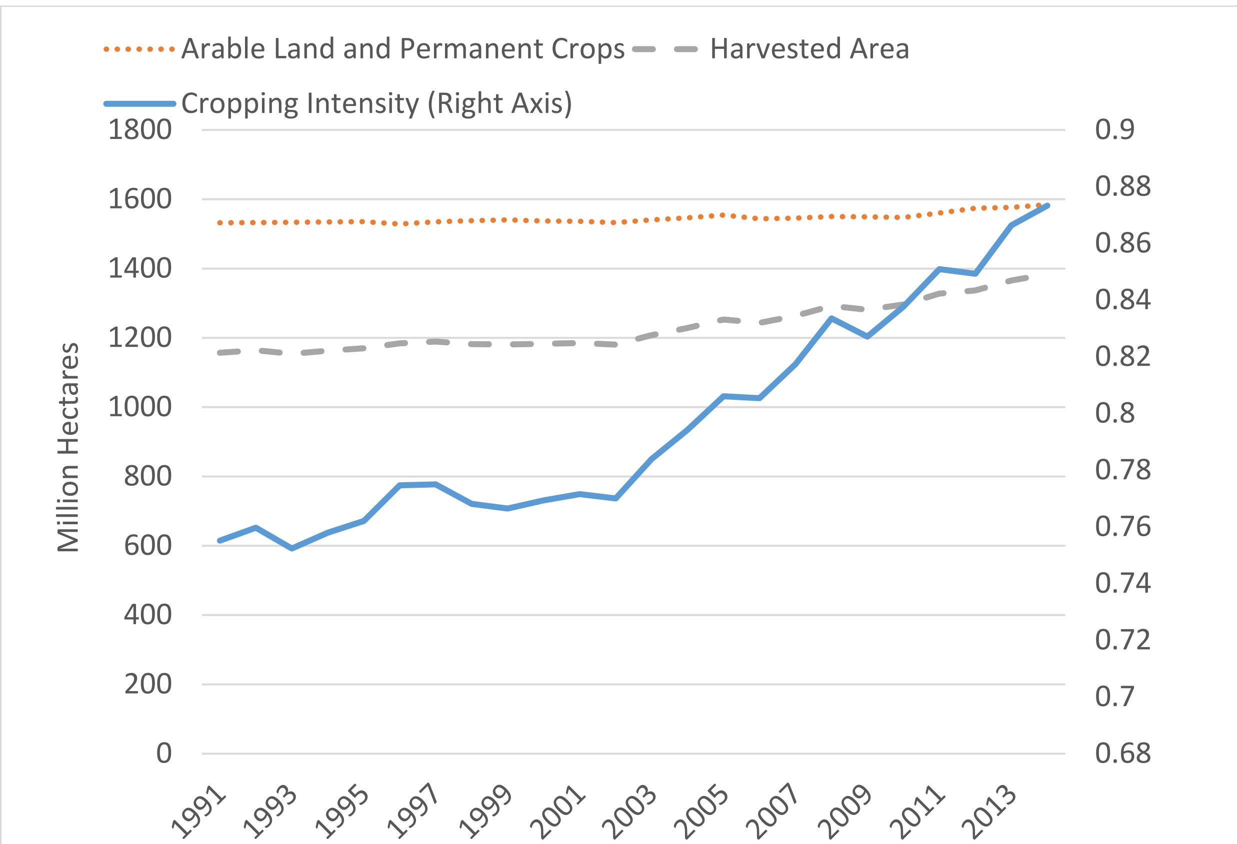

Figure 1 Global Annual Cropland Use and Cropping Intensity

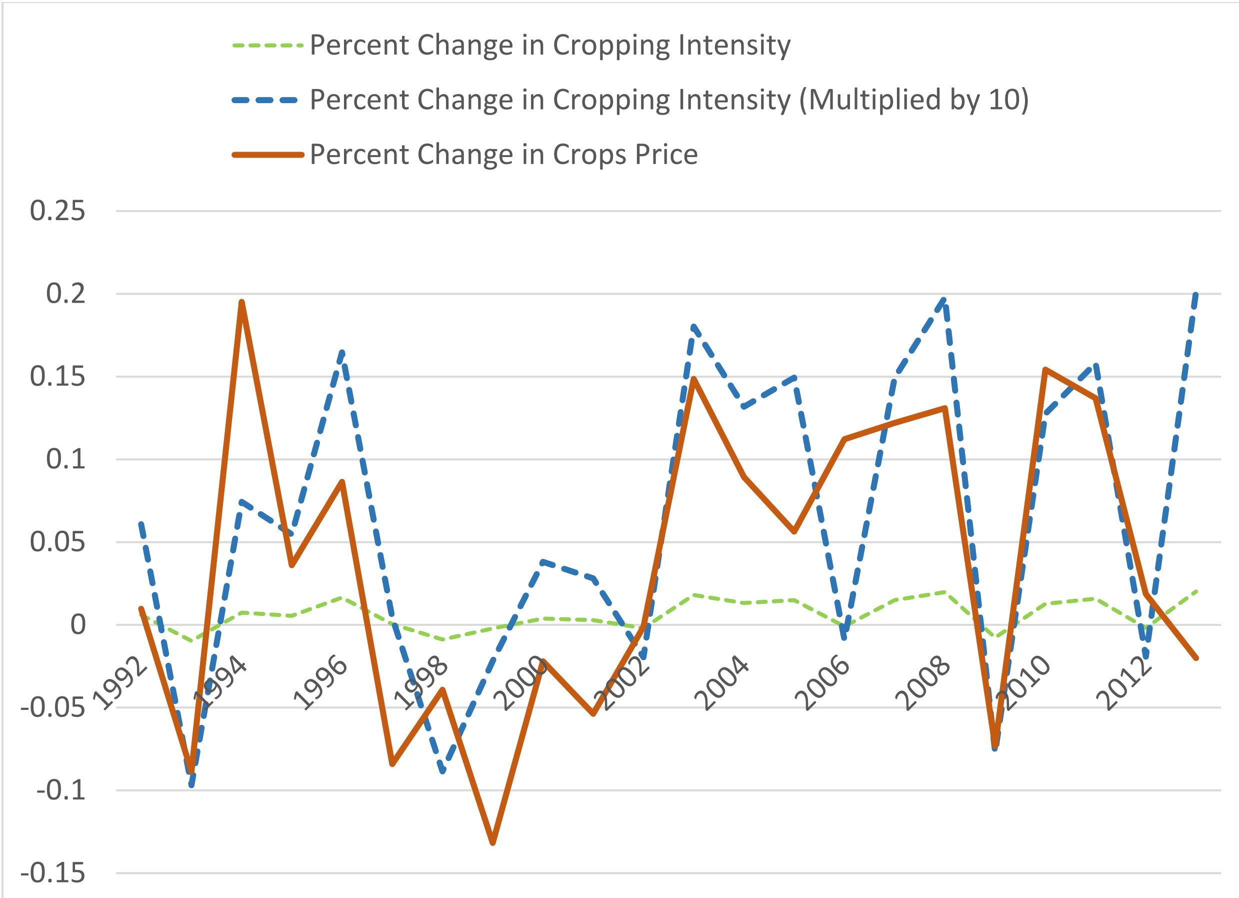

Figure 2 Annual Percent Change in Global Crops Price and Cropping Intensity

Table 1: Land use change following a US ethanol expansion up to 15 BG from the 2004 level, with parameters from Taheripour et al. (2016)

	Without Multiple Cropping Response		With Multiple Cropping Response	
	Change in harvested area (1000 ha)	Change in cropland cover (1000 ha)	Change in harvested area (1000 ha)	Change in cropland cover (1000 ha)
USA	148.1	159.7	537.9	157.4
European Union	33.7	36.5	63.3	30.7
Brazil	66.1	45.7	92.7	41.1
Canada	35.1	40.6	47.8	34.6
Japan	5.6	5.1	5.8	4.3
China	12.4	11.6	57.0	10.2
India	6.9	6.3	47.5	7.1
Central Amer.	4.9	10.9	22.2	9.9

South Amer.	48.7	51.8	81.4	47.9
East Asia	1.6	2.6	4.0	2.7
Mala-Indo	2.4	4.9	11.7	6.1
Rest of S. E. Asia	13.6	12.3	44.8	16.0
Rest of S. Asia	14.3	17.1	20.5	12.9
Russia	12.4	19.0	30.7	16.3
Other CEE-CIS	28.2	33.1	51.6	28.1
Other Europe	0.5	0.4	0.9	0.3
Mid. East & N. Africa	22.4	24.5	37.0	21.4
Sub Saharan Africa	425.0	502.8	398.5	427.9
Oceania	18.4	14.1	38.7	12.4
World	900.3	998.9	1594.1	887.4

Table 2: Land use change following a US ethanol expansion up to 15 BG from the 2004 level, with uniform yield response 0.25

	Without Multiple Cropping Response		With Multiple Cropping Response	
	Change in harvested area (1000 ha)	Change in cropland cover (1000 ha)	Change in harvested area (1000 ha)	Change in cropland cover (1000 ha)
USA	154.0	166.1	554.9	163.3
European Union	35.7	38.7	66.9	32.3
Brazil	72.6	50.1	100.9	44.9
Canada	37.7	43.6	51.2	37.1
Japan	5.6	5.0	5.8	4.3
China	14.7	13.8	64.4	11.9
India	9.8	8.9	54.7	9.4
Central Amer.	5.3	11.7	23.7	10.6
South Amer.	49.1	52.3	82.7	48.3
East Asia	1.6	2.6	4.1	2.7
Mala-Indo	3.1	6.5	12.9	7.5
Rest of S. E. Asia	15.4	13.9	47.7	17.5
Rest of S. Asia	17.8	21.3	24.3	16.2
Russia	12.4	19.0	31.1	16.3
Other CEE-CIS	30.4	35.6	55.1	30.1
Other Europe	0.5	0.4	0.9	0.3
Mid. East & N. Africa	23.9	26.2	39.4	22.7
Sub Saharan Africa	450.8	533.1	420.7	451.5
Oceania	18.6	14.2	39.4	12.5
World	958.8	1063.1	1680.7	939.6

Table 3: Land use change following a US ethanol expansion up to 15 BG from the 2004 level, with uniform land transformation elasticity -0.11

	Without Multiple Cropping Response		With Multiple Cropping Response	
	Change in harvested area (1000 ha)	Change in cropland cover (1000 ha)	Change in harvested area (1000 ha)	Change in cropland cover (1000 ha)
USA	736.4	788.8	1148.9	786.6
European Union	117.5	127.3	127.4	106.4
Brazil	70.5	48.8	95.7	43.7
Canada	139.4	161.1	132.9	135.6
Japan	3.2	2.9	3.8	2.4
China	44.9	41.8	85.1	37.2
India	5.5	5.1	46.1	6.1
Central Amer.	17.0	37.7	33.5	35.4
South Amer.	43.8	46.4	75.2	43.3
East Asia	0.9	1.6	3.2	1.6
Mala-Indo	-1.3	-3.0	8.2	-1.9
Rest of S. E. Asia	3.7	3.3	31.3	4.8
Rest of S. Asia	13.7	16.6	19.4	12.3
Russia	24.3	35.6	37.7	30.1
Other CEE-CIS	94.8	111.1	104.1	94.6
Other Europe	1.6	1.2	1.8	1.1
Mid. East & N. Africa	80.4	88.1	85.4	77.0
Sub Saharan Africa	216.9	259.1	224.9	217.2
Oceania	67.1	51.4	78.7	45.5
World	1680.4	1824.8	2343.2	1679.0

Table 4: Land use change following a US ethanol expansion up to 15 BG from the 2004 level, with uniform land transformation elasticity -0.2

	Without Multiple Cropping Response		With Multiple Cropping Response	
	Change in harvested area (1000 ha)	Change in cropland cover (1000 ha)	Change in harvested area (1000 ha)	Change in cropland cover (1000 ha)
USA	1115.7	1193.0	1518.6	1199.9
European Union	141.5	153.2	143.1	128.4
Brazil	96.4	66.8	115.7	60.3
Canada	169.5	196.3	153.6	162.5
Japan	3.7	3.4	4.0	2.8
China	49.7	47.3	87.0	43.5
India	3.0	2.7	42.4	5.9
Central Amer.	19.6	43.3	35.0	42.2

South Amer.	55.2	58.1	84.3	55.7
East Asia	1.0	1.8	3.2	2.0
Mala-Indo	-4.9	-11.2	4.7	-8.3
Rest of S. E. Asia	1.7	1.6	28.7	4.6
Rest of S. Asia	13.9	17.1	18.5	12.6
Russia	12.6	15.0	26.0	12.3
Other CEE-CIS	115.1	135.0	118.6	115.8
Other Europe	2.0	1.6	2.2	1.4
Mid. East & N. Africa	101.2	110.8	102.1	97.5
Sub Saharan Africa	259.3	310.2	253.6	261.2
Oceania	89.9	68.9	96.8	61.3
World	2246.1	2414.9	2838.0	2261.6

Table 5: Systematic Sensitivity Analysis (SSA): Harvested Area (1000 ha)

	Original	SSA Mean	SSA S.D.	95% CI: LB	95% CI: UB
USA	537.9	534.7	150.8	233.0	836.4
European Union	63.3	62.4	9.7	43.1	81.8
Brazil	92.7	92.1	9.1	73.9	110.3
Canada	47.8	47.5	4.3	38.9	56.0
Japan	5.8	5.8	0.1	5.7	6.0
China	57.0	55.9	15.2	25.6	86.3
India	47.5	46.4	13.5	19.3	73.5
Central Amer.	22.2	21.8	6.1	9.7	34.0
South Amer.	81.4	80.8	11.7	57.4	104.2
East Asia	4.0	4.0	0.8	2.3	5.7
Mala-Indo	11.7	11.5	3.2	5.1	17.9
Rest of S. E. Asia	44.8	44.1	10.9	22.2	66.0
Rest of S. Asia	20.5	20.3	2.0	16.3	24.4
Russia	30.7	30.2	6.2	17.9	42.6
Other CEE-CIS	51.6	50.9	7.8	35.3	66.6
Other Europe	0.9	0.9	0.1	0.6	1.1
Mid. East & N. Africa	37.0	36.7	5.1	26.6	46.8
Sub Saharan Africa	398.5	398.6	10.6	377.4	419.8
Oceania	38.7	38.3	7.1	24.0	52.6
World	1594.1	1582.9	253.2	1076.6	2089.3

Note: S.D., CI, LB, UB denote standard deviation, confidence interval, lower bound, and upper bound, respectively.

Table 6: Systematic Sensitivity Analysis (SSA): Cropland Cover (1000 ha)

	Original	SSA Mean	SSA S.D.	95% CI: LB	95% CI: UB
USA	157.4	157.4	0.8	155.8	159.1
European Union	30.7	30.8	2.1	26.6	35.0

Brazil	41.1	41.2	1.7	37.8	44.6
Canada	34.6	34.7	2.3	30.2	39.2
Japan	4.3	4.4	0.3	3.8	4.9
China	10.2	10.3	0.5	9.2	11.3
India	7.1	7.1	0.2	6.6	7.5
Central Amer.	9.9	9.9	0.4	9.2	10.6
South Amer.	47.9	48.0	1.4	45.1	50.8
East Asia	2.7	2.7	0.0	2.6	2.7
Mala-Indo	6.1	6.0	0.4	5.3	6.8
Rest of S. E. Asia	16.0	15.9	1.3	13.4	18.5
Rest of S. Asia	12.9	13.0	1.5	10.0	16.0
Russia	16.3	16.4	1.0	14.4	18.3
Other CEE-CIS	28.1	28.2	1.8	24.6	31.8
Other Europe	0.3	0.3	0.0	0.3	0.3
Mid. East & N. Africa	21.4	21.4	1.1	19.1	23.7
Sub Saharan Africa	427.9	429.2	27.1	375.0	483.3
Oceania	12.4	12.5	0.6	11.2	13.7
World	887.4	889.2	40.7	807.8	970.6

Note: S.D., CI, LB, UB denote standard deviation, confidence interval, lower bound, and upper bound, respectively.