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# Improving the land use specification in the GTAP model

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# Improving the land use specification in the GTAP model

Kenneth Baltzer[1] and Jesper Kløverpris[2]

***Abstract***

*This working paper documents a development of the standard Global Trade Analysis Project (GTAP) model to improve the way agricultural land supply is represented in the model and to make it more useful for Life Cycle Assessment (LCA) of products. The usefulness of the modifications is demonstrated by analysing changes in global wheat supply and consequences for agricultural land use caused by an increase in US household demand for wheat. We find that the impacts of the modifications are small in terms of the global wheat supply responses, but considerable in terms of land use changes. We therefore conclude that improving the way agricultural land supply is represented in the model is crucial whenever land use changes are of interest, whereas the standard GTAP model is a reasonable approximation in analyses that do not focus on agricultural land resources.*

# 1. Introduction

This working paper documents a development of the standard Global Trade Analysis Project (GTAP) model to improve the way agricultural land supply is represented in the model and to make it more useful for Life Cycle Assessment (LCA) of products. The usefulness of the modifications is demonstrated by analysing changes in global wheat supply and consequences for agricultural land use caused by an increase in US household demand for wheat. We find that the impacts of the modifications are small in terms of the global wheat supply responses, but considerable in terms of land use changes. We therefore conclude that improving the way agricultural land supply is represented in the model is crucial whenever land use changes are of interest, whereas the standard GTAP model is a reasonable approximation in analyses that do not focus on agricultural land resources.

LCA is the discipline of evaluating the environmental impacts of a product over its entire lifetime, from the resources employed in producing the good to the consequences of final disposal. The inter-disciplinary approach of using economic modelling in LCA is a promising way of relaxing some of the simplifying assumptions usually employed in the LCA literature. For instance, commodities are usually assumed to be in perfectly elastic supply in the long run (Weidema, 2003), implying that increasing demand for a product will be met by a corresponding increase in the production of that product without any implications for the supply of other goods. When crops are analysed in LCA, it is usually assumed that the environmental impacts related to land use (transformation and occupation) derive from the spot cultivated by the immediate crop supplier. It is thereby ignored that, in a world with a growing agricultural area, the marginal effect of consuming crops will be transformation and occupation of land at the frontier between agriculture and nature. By utilising the GTAP model to obtain LCA data, we explicitly take into account the global economic consequences of increasing consumption of a product, in terms of international trade, supply of all agricultural commodities, and changes in agricultural land use. The latter in particular is important for assessing the environmental impacts of increased consumption of a crop-based product.

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In order to make the GTAP model useful for LCA analysis, we need to improve the standard model in various ways. Our modifications include:

- Introduction of land supply curves, calibrated on country-specific data on the current utilisation and the potential for expansion of agricultural land
- Adjustment of the standard GTAP specification of agricultural land supply to allow for clearing of land markets measured in physical units (hectares)
- Specification of an exogenous demand shock
- Introduction of demand-driven technological development leading to improved agricultural productivity

The modifications are motivated by the simplified specification of agricultural land markets in the standard GTAP model, in particular the assumption that agricultural land is in fixed supply. In analyses involving agricultural markets this is potentially misleading as there is still scope for expansion of the agricultural area in some regions, particularly in Sub-Saharan Africa and South America (Bot et al., 2000). Relaxing this assumption will improve the realism of the model assumptions, and make it possible to report more plausibly on land use changes. Similarly, the standard GTAP assumption that agricultural land is less than perfectly mobile across sectors introduces a small inconsistency, which makes it impossible to clear land markets measured in physical units (hectares). While we do not attempt to solve this inconsistency once and for all, we propose a simple practical solution to the problem at hand, based on adjustment of some of the standard GTAP variables. Finally, the specifications of an exogenous demand shock and demand-driven technological development are motivated by issues addressed in the LCA literature (as discussed in Kløverpris et al., forthcoming).

This is not the first attempt to develop the land supply specifications of the standard GTAP model. Van Meijl et al. (2006) introduced a land supply curve into the GTAP model calibrated on data obtained from FAO. However, they operate with a single type of land suitable for any kind of agriculture, crop production as well as pasture. We divide agricultural land into two sub-types, cultivable land and grazable land, and specify a van Meijl supply curve for each of the two land types. This extension is motivated by observations that pasture often occupies land, which is unsuitable for cultivation. The underlying assumption of our specification is that cultivable land may be used for any agricultural activity, whereas grazable land is only suitable for pasture and not crop cultivation.

Lee et al. (2005) develops a new land use database, in which land is divided into 18 Agri-Ecological Zones (AEZs) based on climate and precipitation. This development goes a long way towards solving the land market clearing inconsistency in GTAP. Optimally, we would like to utilise this land use database and specify a land supply curve for each of the 18 AEZs, but data needed to construct the land supply curves were not available at this level of detail.

This paper serves as a background document to an article series on the use of economic modelling in LCA analysis to be published in the International Journal of Life Cycle Assessment (Kløverpris et al., forthcoming; submitted). Whereas, the present paper documents the methodological developments in detail, the articles focus on the motivation for combining the two approaches and the use of the results in LCA analysis. Additionally, in Kløverpris et al. (submitted), we analyse a wider range of scenarios, simulating the same demand increase in four different countries, USA, Denmark, Brazil and China, to provide a more nuanced picture of the global land use consequences of increased crop consumption.

The rest of the paper is organised as follows: The next section describes the modifications made to the GTAP model (appendix A presents the modifications in GTAP code) and section 3 documents the modifications to the GTAP database. Section 4 presents a range of scenarios used to demonstrate the effects of the model extensions and section 5 discusses the results. The final section 6 concludes.

## 2. Modifications to the GTAP model

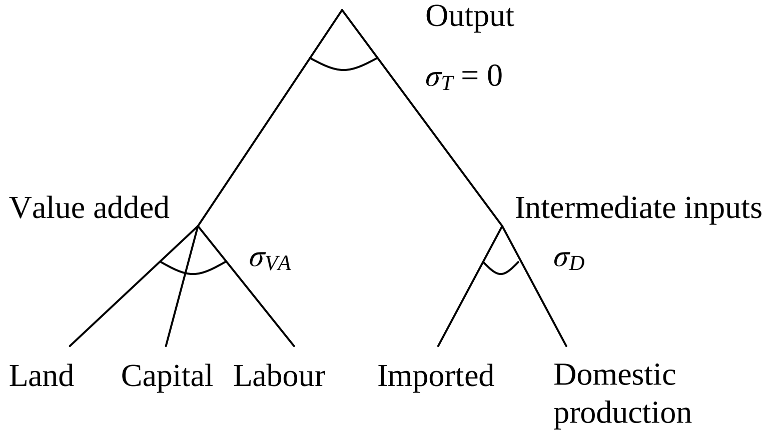
### *The GTAP model: strengths and limitations*

The GTAP model is a computable general equilibrium model specifically designed to analyse trade policy scenarios. As such, it is global in scope, essentially reflecting the whole world economy, with the greatest emphasis on national production structures, bilateral trade flows and various domestic and trade policy instruments. We will not go into detail here about the general specifications of the standard model – full documentation can be found at the project's website (www.gtap.org). Instead, we will discuss the main strengths and limitations of the standard model in relation to our research topic, and how we modify the standard model to better accommodate our needs.

Our motivation for choosing the GTAP model is its global coverage and its ability to simulate changes in worldwide trade flows and production structures in response to exogenous shocks. One of the primary objectives is to analyse land use changes anywhere in the world induced by increased crop demand in a single location. To accomplish this, we need to account for the ways in which the demand shock is transmitted through changes in domestic supply and demand, imports and exports and the production structures of the most important trade partners and competitors. This is what the GTAP model does best.

However, the standard GTAP model does not have a very strong representation of agricultural land markets. All productive sectors in the model are approximated by nested Constant Elasticity of Substitution (CES) functions as illustrated in figure 1. In the bottom nest, primary factors, such as land, capital and labour, combine to produce a value added composite, and for a range of intermediate inputs, such as machinery, fuel and services, a mix of imports and domestic goods produce intermediate composites. The propensities of firms to substitute among primary factors in one nest and imports and domestic goods in the other nest is governed by (constant) elasticities of substitution, respectively $\sigma_{VA}$ and $\sigma_D$ (using standard GTAP notation). In the upper nest, the value added composite combines with all intermediate input composites to generate sectoral output. In standard GTAP applications, the elasticity of substitution between the value added composite and intermediate inputs is assumed to be zero (a so-called Leontief production structure), implying that intermediate inputs and primary factors enter production in fixed proportions.

**Figure 1: Standard GTAP production structure**



The characterisation of land in the standard GTAP model is inappropriate for our purposes. First of all, land (as well as capital and labour) is assumed to be in fixed supply. The only way any given agricultural sector can expand its use of land is through displacement of other crops or livestock. The standard model also enables an alternative closure[3] characterised by perfectly elastic land supply. We need to account for a plausible flexible land supply, which falls in between these two extremes.

Secondly, land is assumed to be a homogeneous but 'sluggish' factor. Land sluggishness is a simplified way of modelling complex land use decisions. It reflects the observation that land use patterns do not respond perfectly to changes in relative land rents (land prices)[4] in different sectors. This implies that land owners only to a limited extent shift land from low-rent to high-rent sectors, and we generally do not find that land rents equalise across sectors. This is also reflected in the GTAP database. However, this specification generates a small inconsistency, which makes it impossible to clear land markets measured in hectares (we discuss this in more detail below). This is seldom a big problem in trade policy analyses as land use changes are of minor interest (reporting land use shifts as percentage changes is usually sufficient). For our purposes, however, accounting for land use changes in physical units (hectares) is important and we need to address this issue.

Finally, we make minor adjustments to the model to be able to simulate the shocks of interest. The standard model does not allow for direct shocks to goods demand or demand-driven technological development. We describe below how to incorporate both.

The following subjections discuss our modifications to the standard GTAP model. For interested readers, the GTAP code implementing all the modifications is detailed in Appendix A.

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[3] Model closure refers to the specification of endogenous and exogenous variables. Mathematically, the model is identified if the number of independent endogenous variables equals the number of equations in the model. The standard closure specifies quantity of land as exogenous (fixed) and the land price is determined endogenously by the model. In the alternative closure, the land price is fixed and land supply adjusts freely to clear land markets.

[4] Please note that we use the terms land rent and land price interchangeably throughout the paper. Assuming perfect competition on land markets, the equilibrium (rental) price on land is equal to the rents generated by the land.

### *Land supply curves*

In the standard model, it is necessary to specify either land quantities or land prices as exogenous (fixed) variables, generating a fixed or a perfectly elastic land supply. Graphically, this could be represented as respectively a vertical and a horizontal land supply curve. Following van Meijl et. al. (2006), we choose instead to allow both the land price and quantities to be endogenous and specify a new relationship between the two variables to close the model. This relationship can be interpreted as a land supply curve.

We define the same land supply curve as van Meijl et al. (2006)[5], using standard GTAP notation (for now, we suppress indices to avoid notational clutter):

$$QO = a - \frac{b}{PM} \tag{1}$$

where $QO$ is land supply (quantities), $PM$ is (real) land price and $a$ and $b$ are coefficients. The coefficient $a > 0$ is interpreted as the total quantity of land potentially available for agricultural production, whereas $b > 0$ determines the shape (curvature) of the land supply curve. In the next section we show how we derive $a$ from external data sources and calibrate $b$ from the GTAP database.

A general equilibrium model is typically non-linear. To facilitate model simulation, the standard GTAP model is transformed into a linear specification by expressing all variable in percentage change form (a levels-version of the model also exists).[6] To linearise (1) we perform total differentiation and get

$$dQO = \frac{b}{PM^{2}} dPM \tag{2}$$

Adopting the convention that lower case variables represent percentage change form, we define $qo = dQO/QO$ and $pm = dPM/PM$ . Using these definitions, (2) can be written as

$$qo = \varepsilon \times pm \tag{3}$$

where

$$\varepsilon \equiv \frac{dQO/QO}{dPM/PM} = \frac{b}{a \times PM - b} = \frac{a - QO}{QO} \tag{4}$$

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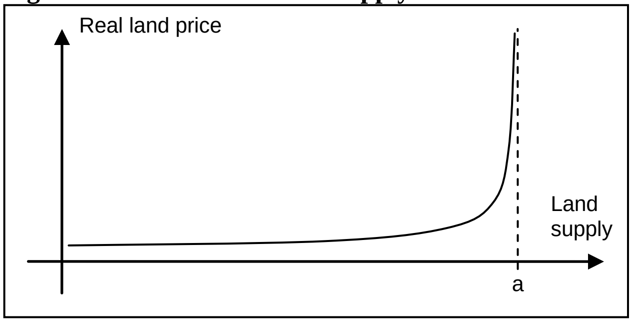
[5] In the original paper by van Meijl et al. (2006), there seems to be a typing error as the equation [land supply = (a – b) / real land price] does not conform to the shape of the land supply curve.

[6] The non-linear features of the model are preserved by splitting the shock into multiple small steps, solving the model and updating all coefficients at each step.

is the elasticity of land supply. The elasticity is not constant but depends inversely on land supply. The land supply curve is illustrated in figure 2.

**Figure 2: Illustration of land supply curve**



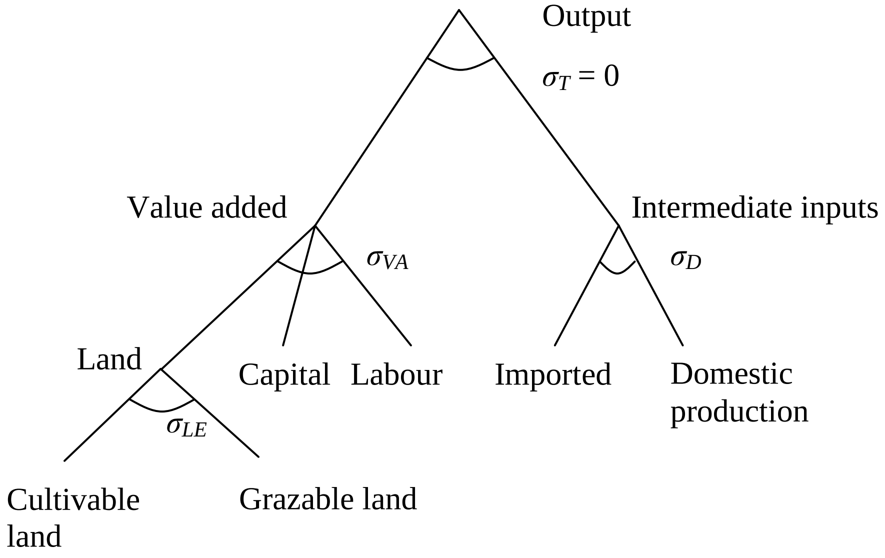
At small land prices, land supply is low and highly elastic, implying that small changes in prices induce a large change in land supply. At the limit with no land under agricultural use, the land supply curve is horizontal (elasticity equal to infinity). This reflects a situation where uncultivated land is readily available, and it is relatively cheap to expand the agricultural area. As land under cultivation increases and asymptotically approaches the total agricultural land potential, prices increase at a growing rate, and land supply becomes more and more inelastic. At the limit, where cultivated land equals the total land potentially available for agricultural use, the land supply elasticity approaches zero, illustrated by a vertical land supply curve. Thus, this land supply curve can be seen as a generalisation of the standard GTAP closure, covering the two extremes of perfectly elastic and fixed land supply as special cases at respectively zero land use and land use equal to total potentially available agricultural land.

### *Disaggregation of land*

Van Meijl et al. (2006) construct a single land supply curve based on FAO estimates of the potential land areas suitable for crop cultivation. However, the land supply curves cover land used for livestock rearing as well as crop cultivation. In our data, we observed several examples of agricultural land areas currently in use outstripping the areas potentially available for cultivation. This suggests that some areas of land in addition to the areas suitable for crop cultivation could be available for livestock grazing.

Consequently, we extent the approach by van meijl et al. (2006) by splitting land into two sub-types, *cultivable land* and *grazable land*, each characterised by its own land supply curve of the form discussed above (figure 2). Cultivable land is designated as land suitable for crop production, whereas grazable land is defined as land, which is too marginal for crop production but suitable as grazing land. This distinction implies that crop producing sectors can use cultivable land but not grazable land, while livestock sectors may use both types of land. The modified production structure is depicted in figure 3.

**Figure 3: Modified production structure**



Crop producing sectors only use cultivable land as input, no substitution between the two types of land is possible, and the production structure resembles the standard model illustrated in figure 1. In livestock sectors, the substitution between cultivable land and potential pastures is governed by a new parameter, the elasticity of substitution $\sigma_{LE} \geq 0$. As we have been unable to obtain estimates of $\sigma_{LE}$ it is arbitrarily set equal to 1. This is larger than the substitutability among primary factors in general ($\sigma_{VA} = 0.23$ in the livestock sector), but the two types of land are less than perfect substitutes (typically approximated by an elasticity of substitution equal to 100). When demonstrating the modifications in the end of this paper, we will experiment with other values of $\sigma_{LE}$.

### *Clearing of land markets in physical units*

The standard GTAP model assumes that land is a homogeneous factor, which produces different land rents in different sectors. This representation of land markets should not be taken as realistic in every detail, but rather be viewed as an approximation, which mimics the outcome of complex land use decisions. However, the specification produces some inconsistencies, when we report land use changes in terms of hectares (rather than percentage changes), as will be discussed in more detail below.

For our purposes, we need to eliminate these inconsistencies. A realistic modelling of land markets would require accounting explicitly for such issues as land heterogeneity, crop rotation and seasonality. We would have to make substantial modifications to the standard model and database, placing heavy demands on availability of data. The work done by Lee et al. (2005) on developing a new land use database goes a long way towards this goal, but we would still require detailed data on the potential for agricultural land expansion in order to construct land supply curves. Such an approach is beyond the scope of this paper. Instead, we attempt to obtain clearing of land markets in physical units by making slight adjustments to standard GTAP land supply. Before going into the details of our approach, we briefly discuss why this is necessary.

In the standard GTAP model, land is assumed to be imperfectly mobile across agricultural sectors, i.e. the conversion of land from one use to another is characterised as ‘sluggish’. Due to this imperfect mobility, land rents fail to equalise across sectors. The sluggishness is represented by a

Constant Elasticity of Transformation (CET) function. Originally, this functional form was developed as a concave analogue to the Constant Elasticity of Substitution (CES) function and is typically used to model the production possibility frontier[7] of products using the same scarce resources (Powell and Gruen, 1968). In GTAP, it is used to model the 'transformation' of land supply from one sector to another. To provide a slightly abstract analogue to the typical use of the CET as a production possibility function, we can say that the common resource, total land supply, is used to 'produce' a number of sectoral land supplies, one for each agricultural sectors. Thus, the CET forms a 'land supply frontier' rather than a production possibility frontier.

In its general two-product form, the CET function is given as

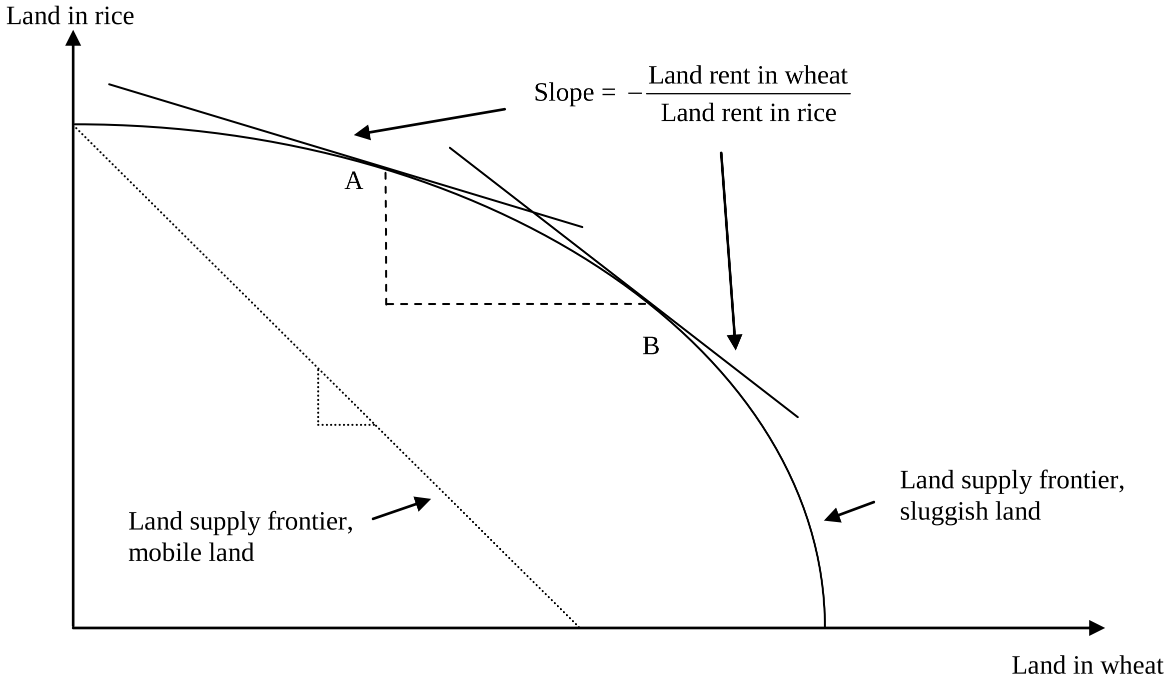
$$x_1^{1-1/\tau} + a x_2^{1-1/\tau} = b \; 1-\tfrac{1}{\tau} \qquad (5)$$

where $x_i$ ($i$ = 1,2) are the two products, $\tau$ is the constant elasticity of transformation, $a$ is a product-biased shifter and $b$ is a product-neutral shifter. In GTAP, $\tau$ = -1 (this is the parameter ETRAE in GTAP) and (5) simplifies to

$$x_1^2 + a x_2^2 = 2b \qquad (6)$$

where $x_i$ is now interpreted as land supply in two different agricultural sectors. The parameters $a$ and $b$ can be calibrated using the GTAP database. The CET function is depicted in figure 4.

**Figure 4: The CET function representing land supply in standard GTAP**



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[7] The Production Possibility Frontier is a common term in economic theory. It represents the largest combination of goods that can be produced given the scarce resources available. In this context, the 'frontier' simply denotes the boundary between what is physically possible and what is not.

Consider an economy, in which two sectors, wheat and rice, use land in production. The land supply frontier generated by the CET function describes the possible allocations of land in the two sectors. The optimal allocation of land is the one that maximises total land rent and is determined by the relative land rents in the two sectors. In figure 4, it is illustrated by the point of tangency between the land supply frontier and a line representing total land rents. If per hectare land rents in the rice sector is higher than in wheat cultivation, most land will be allocated to the production of rice as at point A. Suppose now that the land rents in the wheat sector increase due to higher demand for wheat. This is represented by a steeper land rent line and the optimal allocation of land moves to point B. Some of the land under rice cultivation is converted to wheat land. However, the area of land received by the wheat sector is larger than the amount of land removed from rice cultivation. A hectare of rice land is 'transformed' into more than a hectare of wheat land.

The implication of this specification is that the aggregate of sectoral land supply does not equal total land supply when measured in physical units, i.e. land markets do not clear. For instance, the model may provide a solution where land under rice cultivation is reduced by 100 hectares and land used for wheat production increases by 120 hectares, while at the same time total land supply is unchanged. In GTAP, this can still provide a general equilibrium solution because (the change in) sectoral land supply is aggregated by using value-weights rather than quantity-weights. As long as per hectare land rents vary across sectors, different weights are used in different sectors.[8] In the example above, change in land under rice cultivation receives a larger weight (1.2) than change in wheat land (1) such that the weighted aggregated change sums to zero.

One way to fix this inconsistency could be to assume that land is homogeneous and perfectly mobile across sectors. This could be interpreted as a special case of the CET function with the constant elasticity of substitution approaching negative infinity, generating a linear land supply frontier with a slope of -1 (a downward sloping 45º line). Per hectare land rent would be equalised across sectors, and a small change in land rent in one sector would instantly cause a change in land use to restore land rent equalisation. Any movement along the line would transform land from one sector to another on an equal hectare-by-hectare basis. However, this approach poses two problems. Firstly, results would change considerably, making agricultural supply much more responsive to changing prices than what is typically observed on agricultural markets. This would imply that a particular area of land would be equally suitable for cultivation of wheat and rice, which is not very plausible (in fact, this is one of the main reasons for the sluggish specification). Secondly, we would need to modify the database substantially to reflect the assumption that per hectare land rents are equalised across sectors (in the standard GTAP database, per hectare land rents show significant variation across sectors).[9]

We wanted to find a way to solve the problem, which affected the main results of the standard model as little as possible. Our solution is to define a new variables representing land supply measured in physical units constructed as an adjustment of the standard GTAP variables, such that sectoral land supply aggregates to total land supply using quantity weights. In the standard model,

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[8] In the GTAP model, the percentage change in aggregate land supply equals the *value-weighted* sum of percentage changes in sectoral land supply. To generate a consistent land market clearing measured in physical units, this sum should be *quantity-(hectare-)weighted* instead. The weighting by value is a mathematical implication of the CET-function as illustrated in figure 4. This can be shown by solving the land owner's problem of maximising total land rent and linearise the resulting land supply curves.

[9] We did try to follow this approach, but gave up as the modifications needed were beyond what we would consider reasonable.

the variable *QFE*(“*land*”,*j*,*r*) is the quantity of land demanded by sector *j* in region *r*. This is the variable depicted along the axes in figure 4. We define a new variable, *LDM(i,j,r),* as the adjusted sectoral supply of land measured in physical units, linked to the standard GTAP variable by

$$QFE(i,j,r) = PSF(i,r) \times LDM(i,j,r) \quad (7)$$

where *PSF(i,r)* is an *adjustment scaling factor*. Note that *j* is missing from the index on *PSF(i,r)*, implying that we apply the same factor of adjustment in all sectors. At the aggregate level, we have a similar relationship between the standard GTAP variable representing aggregate supply of land, *QO(i,r),* and our adjusted measure of land supply, *LSP(i,r),* defined by

$$QO(i,r) = APF(i,r) \times LSP(i,r) \quad (8)$$

where *APF(i,r)* is the analogue of *PSF(i,r)* at the aggregate level. Finally, we have the market clearing condition on land markets requiring the aggregate of sectoral land supply to equal total land supply. We can write this as

$$LSP\ \ i,r\ = \sum\nolimits_j LDM\ \ i,j,r \quad (9)$$

It is clear that the adjustment variables, *PSF(i,r)* and *APF(i,r)*, are closely related. If we insert (7) and (9) into (8) we get

$$QO(i,r) = \frac{APF(i,r)}{PSF(i,r)} \sum_j QFE(i,j,r) \quad (10)$$

Without loss of generality we can normalise *APF(i,r)* to unity. The adjustment is illustrated in 5.

**Figure 5: Adjustment of land supply to clear land markets**

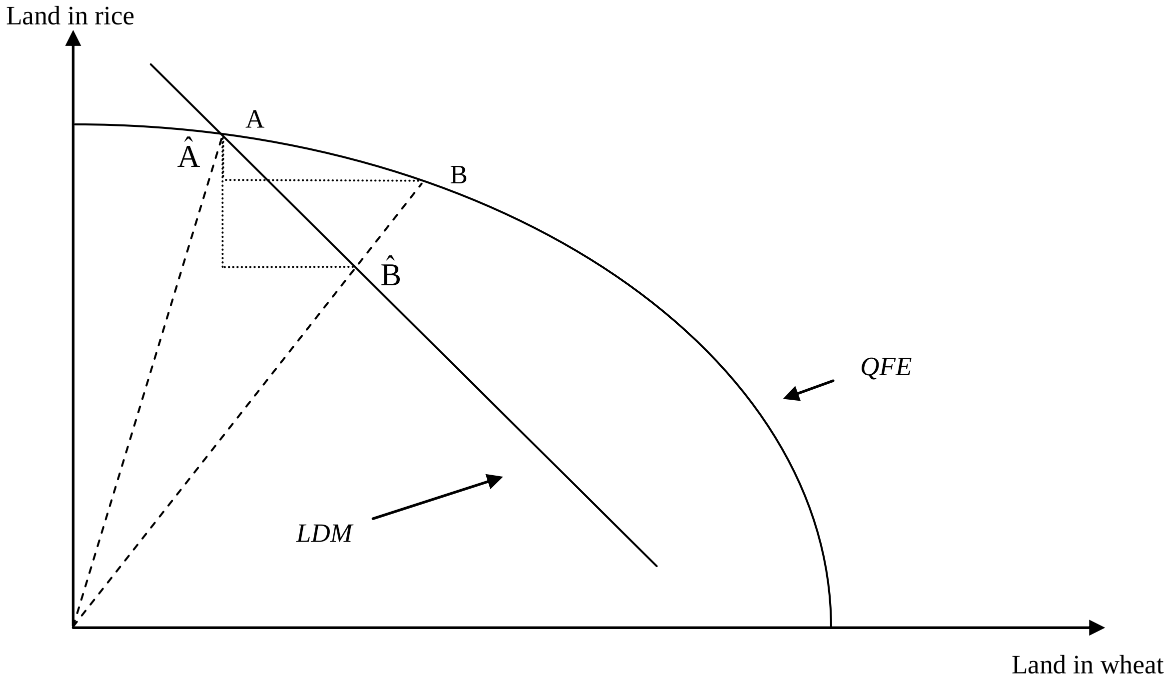

Figure 5 reproduces the illustrative example from figure 4, depicting the change in land use from point A to point B. As before, the concave land supply frontier shows the possible allocations of total land supply across sectors as represented by the standard GTAP variable, *QFE(i,j,r)*. The straight (45º) downward sloping line represents the possible allocations of land measured by hectares and given by *LDM(i,j,r)*. The position of the *LDM*-line in the graph is determined by the initial value of *PSF(i,r)*. Since the GTAP model is formulated in percentage-change form, the initial value of *PSF(i,r)* is irrelevant, and we can normalise it to unity. This normalisation implies that in the initial situation, *QFE(i,j,r) = LDM(i,j,r),* placing the *LDM*-line through the point A in Figure 5.

We apply the same factor of adjustment, *PSF(i,r)*, in all sectors. This implies that the adjusted sectoral land supply measured in hectares may be found at the intersection of the LDM-line and a ray going from the origin to the point of unadjusted land supply allocation. More specifically, in figure 5 the sectoral land supply measured in hectares linked to allocations A and B are respectively $\hat{A}$ and $\hat{B}$ (and due to our normalisation of *PSF(i,r)*, $A = \hat{A}$). Since both points lie on the LDM-line, the adjusted reduction in land use in the rice sector is the exact same size as the adjusted increase in land use in the wheat sector.

It is important to emphasise that *PSF(i,r)* is constructed as an 'artificial' wedge, or 'fudge factor', between the standard GTAP variable, *QFE(i,j,r)*, and our measure of land in physical units, *LDM(i,j,r)*. Its sole purpose is to make land market clearing possible, i.e. to ensure that one hectare of land in one sector is converted to one hectare of land in another. Therefore, it has no theoretical underpinning. Even so, we can provide a loose interpretation of the adjustments made. We interpret *QFE(i,j,r)* as the *productive capacity of agricultural land* rather than land measured in physical units. It is *QFE(i,j,r)* and not *LDM(i,j,r)*, which enters the production function and generates output.

The concavity of the standard GTAP land supply frontier ensures that a mixed allocation of land to all agricultural sectors generates a larger productive capacity, resulting in higher agricultural yields per hectare, than allocating all land to one particular sector. This specification may be interpreted in two ways. First, the productive capacity of land differs from physical land because agricultural land areas have different characteristics (such as soil composition, climate and other geographical conditions), and because the suitability of land characteristics differ across crops. The landowner (the country or region) is assumed to possess a varied portfolio of land with different characteristics - some areas are more suitable for rice cultivation, while others are more appropriate for the production of wheat. If the landowner allocates all land to the cultivation of one rice, he will generate a relatively poor output on the areas of land that are more suitable for cultivating wheat, thus reducing average yields. On the other hand, if he chooses to allocate land to both sectors, he has greater flexibility in allocating the most suitable land areas to each crop, and may therefore obtain higher average yields than specialising in single crops.

The second explanation interprets the cropping patterns displayed by the GTAP model as averages across multiple seasons. If the same single crop is cultivated season after season, average agricultural yields tend to fall (e.g. due to persistence of crop specific pests). However, utilising crop rotation to allocate land across multiple crops helps preserve high agricultural yields. Thus, if equally allocated land across different sectors is seen as an average over several seasons with crop rotation, the larger productive capacity may simple be interpreted as limiting productivity reductions of monoculture.

We will not attempt to describe the complex land use decisions in any detail. Nor will we define more precisely the initial distribution of land qualities within each sector. We simply assume (as does the standard GTAP model) that the CET-function is a reasonable approximation of the possible allocations of the productive capacity of land across sectors. The equations that enter the GTAP model are found by linearising (7) - (9) to obtain (using standard lower-case convention):

$$qfe(i,j,r) = psf(i,r) + ldm(i,j,r) \tag{11}$$

$$qo(i,r) = apf(i,r) + lsp(i,r) \tag{12}$$

$$lsp(i,r) = \sum_j \left[ ldm(i,j,r) \frac{LDM(i,j,r)}{\sum_k LDM(i,k,r)} \right] \tag{13}$$

Equations (11) and (12) are pretty straightforward and equation (13) simply states that the percentage change in total land supply equal the hectare-weighted average of the percentage change in supply of land in each sector. The extension is, however, not completely identified yet. Just as we normalise *APF(i,r)* to unity, we need to specify a rule for its percentage change. In this paper, we apply the closure

$$apf(i,r) = 0 \tag{14}$$

This closure implies that the productive capacity of total land supply, *QO(i,r),* is always equal to the total land supply measured in physical units, *LSP(i,r).* Thus, if a shock expands total land supply, the LDM-line and the QFE-curve move outwards by the same rate. The interpretation is that average agricultural yields per hectare do not change due to land expansions. However, an alternative closure has a potential for capturing the effects of marginal lands, if linked to changes in total land supply. For instance, a (small) negative relationship between *apf(i,r)* and *lsp(i,r)* would lower the average productive capacity of all land (and thereby average yields per hectare), thus simulating the expansion of agriculture onto less fertile lands. If there is evidence to suggest that marginal lands are a greater concern in some regions than in others, it is possible to specify different relationships for each region. However, this has not yet been tested.

### Exogenous demand shocks in households and industries

The main purpose of this paper is to model the consequences on global land use of an exogenous increase in demand for crops. It turns out that results vary significantly depending on the characteristics of the demand shock. For instance, an increase in demand for wheat caused by expanded production of ethanol in the EU would have different implications than an increase in demand for coarse grains by the livestock industry. Therefore, any analysis should model the particular type of shock as closely as possible. However, for the purpose of demonstrating the outcome of the model developments we have made, we specify two types of fairly general exogenous increases in demand for wheat, one by the private households and one by the food processing industry.

The standard GTAP model does not allow for exogenous demand shocks and a small modification is needed. We model the exogenous change in demand as preference or input demand shifts – for unspecified reasons, the private household or the food processing industry find it optimal to demand a greater quantity of wheat. To ensure that the household or food industry observe their budget constraints, we reduce their demand for all other commodities proportionately (by the same percentage).

### Demand-driven technological development

Kløverpris et al. (forthcoming) suggests that technological development in agriculture may be partly exogenous, partly endogenous. Some technological development progresses at a steady pace. Pioneering farmers have a constant incentive to improve their practices to reap the benefits of a higher output at given prices. When the larger output depresses agricultural commodity prices, other producers have to improve yields as well to stay competitive. In modelling terms, this can be characterised by exogenous technological development – progress which is independent of the simulation.

In addition, we can talk about endogenous technological development, i.e. improvements driven by the expansions in demand. Increasing demand for crops puts pressure on the available agricultural area and induces efforts to improve agricultural yields per hectare. To simulate this effect, we create a relationship between the aggregate per hectare land rents (land price) on cultivable lands and the standard GTAP variable representing factor (land) augmenting technological development.

$$afeall("cult.", j, r) = \delta \times \min\ 0, pm("cult.", r) - pfactwld \qquad (15)$$

where *afeall(”cult.”, j, r)* is the standard GTAP variable representing technological development on cultivable land in sector *j* in region *r*, *pm(”cult.”, r)* is the aggregate price of cultivable land in region *r*, *δ* is the technological elasticity, representing the strength of the relationship between the land price and technological development, and *pfactwld* is the models numeraire (subtracting *pfactwld* from the market price ensures that technological development reacts to changes in real rather than nominal prices – this is included to ensure that model homogeneity is preserved). The relationship is specified asymmetrically, such that only increases in the land price affect technological development – there is no technological regression if the land price declines. We have no empirical estimates of the strength of this relationship, so we have arbitrarily chosen a value of $\delta = 0.5$, which is significant but not too high. Thus, a 1 percent increase in the land rents induces a 0.5 percent increase in technological development. Technological development is defined in such a way that 100 hectares of land with 1 percent technological development is equivalent to 101 hectares of land with no improvement.

## 3. Modifications to the GTAP database

The GTAP database is specifically designed for use with the GTAP model. Whereas the model describes the economic relationships in theoretical terms, the database provides the evidence needed for applying the model to the existing global economy. The database can be seen as a snapshot of the global economy, taken at a particular point in time. It consists of values (measured in millions of US$) of a wide range of economic flows, including bilateral trade, production, use of intermediate goods and production factors, final consumption by governments and private households, as well as policy instruments in the form of taxes, tariffs and subsidies. In addition, it provides estimated parameters determining the behavioural relationships in the model. The data originate from national Social Accounting Matrices (basically Input-Output tables), which have been reconciled with international trade flow data obtained from UNCTAD. The GTAP database is fully documented in Dimaranan (2006).

In this paper, we apply the latest database, version 6, based on the year 2001 (version 7, based on 2004, is currently under construction). This version disaggregates the global economy into 87 regions, 57 economic sectors and five primary production factors[10]. For reasons of computational tractability, we aggregate the database into 22 regions and 15 economic sectors as listed in tables 1 and 2.

**Table 1: Regional aggregation used in the paper**

| Abb. | Region | Abb. | Region |
|---|---|---|---|
| aus | Australia | mex | Mexico |
| xoc | Rest of Oceania | xca | Rest of Central America |
| chn | China | per | Peru |
| xea | Rest of East and South-East Asia | bra | Brazil |
| jpn | Japan | xla | Rest of South America |
| xsa | Rest of South Asia | dnk | Denmark |
| ind | India | xeu15 | Rest of EU15 |
| xme | Middle East and North Africa | eu12 | New EU members |
| can | Canada | xer | Rest of Europe |
| usa | USA | xsc | South African Customs Union |
| xsu | Rest of Former Soviet Union | xss | Rest of Sub-Saharan Africa |

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[10] The full list of GTAP regions and sectors may be found at the GTAP website, www.gtap.org.

**Table 2: Sectoral aggregation used in the paper**

| Abb. | Sector | Abb. | Sector |
|---|---|---|---|
| pdr | Paddy rice | ctl | Bovine cattle, sheep and goats, horses |
| wht | Wheat | oap | Animal products nec* |
| gro | Cereal grains nec* | rmk | Raw milk |
| v_f | Vegetables, fruit, nuts | wol | Wool, silk cocoons |
| osd | Oil seeds | food | Food processing |
| c_b | Sugar cane, sugar beet | mnf | Manufacturing |
| pfb | Plant-based fibres | svc | Services |
| ocr | Crops nec* | | |

* not elsewhere classified

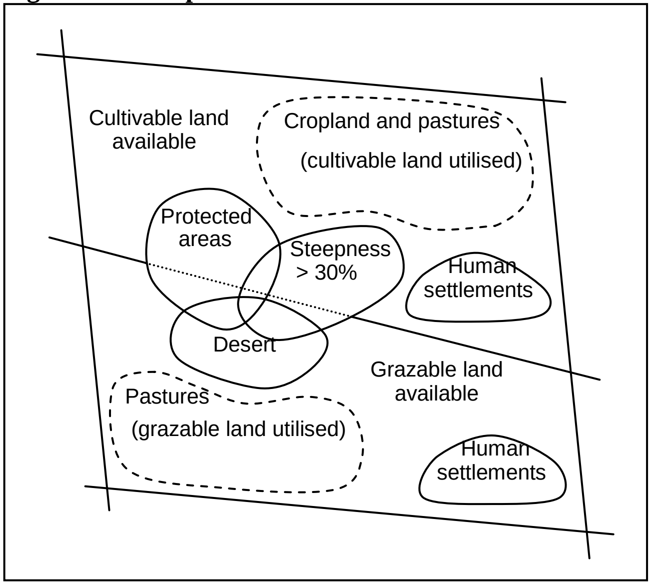
We modify the standard database to reflect the development of the GTAP model and to update the trade structure of the database. We will discuss each of the modifications in turn.

### *Estimating land potentials and utilisation ratios*

The new land supply functions require data on current use of land for crop cultivation and pasture ($QO$ in equation (4)) as well as the maximum potentially available area of land suitable for the two types of uses ($a$ in equation (4)). At this point it may be instructive to emphasise our distinction between the different land use terms, cropland, pasture, cultivable land and grazable land. As discussed above, the terms cultivable land and grazable land refer to two different types of land designated by land characteristics. Following Ramankutty et al. (2002), we assume that cultivable land has the characteristics necessary, such as sufficient precipitation and temperature and suitable soil conditions, to allow rain-fed cultivation of crops. Grazing of livestock is less intensive and thus less demanding on land characteristics. Therefore, in our definition grazable land is unsuitable for crop cultivation, for instance due to too infrequent precipitation, but may still support grazing of livestock. In contrast, the terms cropland and pasture refer to the activity on land rather than land characteristics. Cropland is defined as the area of land currently used for crop cultivation. Similarly, pasture is designated as the area of land currently used for grazing of livestock. It follows that cropland may only occupy cultivable land, whereas pasture may take place on both cultivable and grazable land.

The data requirements and manipulations performed on the raw data is conceptually summarised in figure 6.

**Figure 6: Conceptual illustration of land in the modified GTAP model**



Suppose a country's entire land area is represented by the diamond-shaped form in figure 6. The land area can be divided into cultivable land and grazable land. Ramankutty et. al. (2002) creates a global map of country-specific land areas potentially suitable for cultivation, based on a range of criteria, including climate, precipitation and soil conditions. This map forms the basis for our measure of (unadjusted) potential cultivable land. Unfortunately, similar data were not available for potential gazable land. As a consequence, we assume that the entire land area, not designated as cultivable land can be characterised as (unadjusted) potential grazable land. This may overestimate the extent of potential grazable land, but it is the best estimate we have at this point.

Both types of land potentials are further adjusted for factors not accounted for by Ramankutty et. al. (2002), namely human settlements, protected areas and steep hill or mountain slopes. In the case of potential grazable land, we further adjust for lack of precipitation.[11]

***Human settlements:***

We follow the approach taken in a similar exercise by Bot et al. (2000), who assume that human settlements on average occupy 33 hectares per 1,000 inhabitants. Country-specific population data are found in the latest UN demographic yearbook (2004).The total area of human settlements in each country is not evenly occupying cultivable and grazable land. We use estimates of population distribution onto areas with different degrees of precipitation provided by Bot et al. (2000). In this particular case, we assume that our measure of grazable land is roughly equivalent to Bot et al.'s definition of drylands. Hence, the share of population living in drylands determines the distribution of human settlements onto cultivable and grazable lands.

***Protected areas:***

We assume that protected areas (natural reserves) are not available for cultivation or grazing and are therefore removed from our measures of agricultural land potential. Data on protected areas are

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[11] In the adjustment process we combine data from different sources that are not necessarily directly compatible due to different methods of constructing the data. To avoid any mismatch between data sources, the only data measured in hectares are provided by Ramankutty. All other data sources are measured in shares. For instance, the adjustment for protected areas provided by a UN database is calculated as a share of total land area and not in hectares.

obtained from the United Nations List of Protected Areas (IUCN, 2003) and the online World Database on Protected Areas. The database provides country-specific information on protected areas (measured in hectares), from which we can calculate the share of the total land area designated as protected. However, we have no information on the distribution of protected areas onto cultivable and grazable lands and areas unsuited for any agricultural use (e.g. deserts and mountains). We therefore assume that protected areas are proportionately distributed across land types. For instance, if 15 percent of a country's area is protected, we assume that 15 percent of its potential cultivable and grazable land areas are protected.

***Desert and steepness:***
Country-specific data on deserts, defined as areas with a Length of Growing Period of 0 days, and steeplands, defined as slopes above 30 percent inclination, are found in Bot et al. (2000). We only adjust potential grazable lands for deserts, since the data on potential cultivable land provided by Ramankutty already accounts for (lack of) precipitation. As we have no data on the distribution of steep slopes on the two types of land, we assume that they are proportionately distributed in a similar way as protected areas.

The country-specific adjusted measures of potential cultivable and potential grazable land provide our estimate of the coefficient *a* in equation (4). Data on current use of land for crop cultivation (cropland) and pasture are obtained from Ramankutty, et al. (forthcoming).[12] However, this is not sufficient for estimating total area of cultivable land and grazable land in use (i.e. QO in equation (4)). Whereas croplands only occupy cultivable land, pasture may be found on both land-types. Thus, cultivable land in use includes both cropland and a part of pasture, while grazable land in use consists of a fraction of the area used for pasture. To estimate total use of cultivable and grazable land we need data on the area of cultivable land used for pasture. This information was kindly provided by Dr. Navin Ramankutty of McGill University, Montreal, Canada, who overlaid a global map of cultivable land (Ramankutty et al. 2002) and a global map of cropland and pastures (Ramankutty et al. 2007).

To summarise the data we can calculate land utilisation rates, defined as the share of potential cultivable and grazable land currently in use. These rates calculated at the chosen level of aggregation are presented in table 3 (utilisation rates as well as detailed data on land use, potential land availability and adjustments at the disaggregated country-level are proved in appendix B).

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[12] The data provided by Ramankutty et al. (2002) and Ramankutty et al. (2007) are compatible, so it poses no problem to combine the land data measured in hectares.

**Table 3: Land utilisation rates in GTAP regions (percent)**

| | Utilisation rates | | | Utilisation rates | |
|---|---|---|---|---|---|
| | Cult. | Graz. | | Cult. | Graz. |
| Australia | 64 | 81 | Mexico | 84 | 100 |
| Rest of Oceania | 32 | 43 | Rest of Central America | 93 | 76 |
| China | 100 | 100 | Peru | 34 | 26 |
| Rest of E and SE Asia | 95 | 44 | Brazil | 67 | 17 |
| Japan | 39 | 0 | Rest of South America | 82 | 84 |
| Rest of South Asia | 100 | 61 | Denmark | 100 | 31 |
| India | 96 | 6 | Rest of EU 15 | 92 | 20 |
| Middle East and North Africa | 88 | 100 | Central and E European EU members | 100 | 31 |
| Canada | 70 | 2 | Rest of Europe | 90 | 4 |
| USA | 100 | 62 | S African Customs Union | 100 | 100 |
| Rest of former Soviet Union | 88 | 11 | Rest of Sub-Saharan Africa | 76 | 41 |

Table 3 shows great variation in the availability of unused, suitable land across regions. We have noted that some of the utilisation rates for cultivable lands, in Japan, Peru and Rest of Oceania (mainly New Zealand), are implausibly low. The characteristics of these regions as relatively mountainous lands lead us to believe that we underestimate the adjustments for steep slopes and therefore overestimate the availability of potential cultivable land. For lack of better data and as these regions are not the focus of our present analyses, we have not attempted to correct this.

Many regions, including Europe, North America and Asia, show close to full utilisation of cultivable land combined with a fairly low utilisation of potential grazable lands. This does not necessarily imply a very limited potential for expansion of crop cultivation in these regions. A significant part of cultivation land is occupied by pasture, which could be moved onto grazable lands to release land for cultivation. This mechanism is modelled by the modifications discussed in the previous section.

### *Adjusting land rents*

The standard GTAP database contains data of the value of land used in agriculture, i.e. land rents. This data is needed for the model to run, but precise estimates are hard to obtain. In theory, land rent is the rental price of land, i.e. the ‘fee’ paid by the producer to the land owner for the right to using the land. In practice, the producer is often also the land owner, as well as owner of capital and (his own) labour. Thus, the surplus (value-added) received by the farmer is a mix of land rent, wage and returns on capital investment. The GTAP database decomposes value-added into payments for rent of primary production factors at a regional level, but is unable to identify any sectoral variation reflecting different factor intensities within agriculture in each region. It is therefore assumed that this decomposition is identical across agricultural sectors. For instance, the database estimates that in Denmark 13 percent of the value-added received by the farmers is classified as land rent, whereas 47 percent is capital rent, and 40 percent is wage. This distribution is identical for all agricultural sectors.

We do not possess any more detailed data than what is already in the database. However, we make a small land rent adjustment, which has already been suggested elsewhere in the GTAP community (Lee, et al. 2005). Two of the agricultural sectors, oap (Animal Products, nec) and wol (Wool and silk cocoons) do not use land directly. The first sector consists mainly of pigs and poultry, which are for the major part raised in stables and not on free range. The latter sector is mainly wool from sheep, which are already accounted for in the ctl sector (Bovine cattle, sheep and goats, horses). We removed land rents from these two sectors and added them to capital rents to preserve total value added.

### *Updating the standard GTAP tariffs*

A large number of developments in international trade have taken place since the base year of the version 6 database, 2001. We perform a model simulation of some of these developments, to create a baseline database, which more accurately reflects the current global economy. The developments simulated are:

- Accession of China into the WTO: We adjust Chinas applied tariffs towards other WTO members in accordance with the accession agreement.
- The final implementation of the Uruguay commitments for developing countries: By 2001, some developing countries had not yet phased in all of their tariff reduction commitments. Tariffs for these members were adjusted accordingly.
- The enlargement of the EU with 12 new Central and Eastern European member countries: We removed all internal tariffs, adjusted the new members' tariff schedule to reflect EU tariffs and changed the tariffs of all non-EU countries towards the new members.
- The Everything But Arms (EBA) agreement between Least-Developed Countries (LDCs) and the EU: We removed all EU external tariffs towards LDCs in accordance with the agreement.

## 4. Scenarios

To demonstrate the effects of introducing the modifications discussed in this paper, we simulate an increase in the demand for wheat of 500.000 tonnes in the USA. We specify a 'core' experiment and a number of 'sensitivity'-scenarios demonstrating the impact of various changes in model assumptions and closures. Unless otherwise specified we apply the standard GTAP assumptions in all areas, except one: we use double standard Armington elasticities.

The Armington elasticities represent product homogeneity based on origin of production. The GTAP model operates on the Armington assumption, stating that 'like' products produced in different countries are imperfectly substitutable. Thus, wheat produced in Denmark is viewed as a different commodity than US wheat, and may therefore command a different price on the market. The Armington assumption not only approximates differences in product characteristics (quality, safety, physical attributes), but captures a wide range of sources of inertia in the trade patterns, such as search and contracting costs, home product bias, etc. The higher the Armington elasticities, the greater the propensity to shift trade patterns in response to changes in relative prices.

There is an ongoing debate regarding the most appropriate size of Armington elasticities. The standard GTAP elasticities are empirically estimated (Hertel, et. al. 2004). However, some analysts claim that those parameters are too low and propose the use of Armington elasticities that are double standard GTAP or even higher (see e.g. Harrison, et. al. 2004). Much evidence suggests that long run Armington elasticities tend to be higher than short term (McDaniel and Balistreri, 2002) due to inertia in the trade patterns. To reflect the long term perspective usually taken in LCA studies, we apply double standard Armington elasticities (standard elasticities are presented in Dimaranan, 2006).

*Core scenario*

In our core scenario, we shock US household demand for wheat by 500,000 tonnes. We include the land supply curve specified in this paper, but the endogenous relationship between land prices and technological development is switched off. We compare the results of the core scenarios with standard GTAP closure specifying fixed supply of land (vertical supply curve) as well as the 'alternative' closure assuming perfectly elastic supply of land (horizontal supply curve).

*Sensitivity scenarios*

We simulate four sensitivity scenarios to demonstrate the impact of alternative assumptions. Each scenario analyses one departure from the core scenario:

1. Food industry: The core scenario places the demand expansion in the private households to make as 'neutral' a demand shock as possible. However, very little wheat is actually demanded directly by the households as most of it is further processed by the food processing industry before final consumption. We simulate an expansion in food industry demand for wheat by 500,000 tonnes and see how results change.
2. Endogenous technological development: This scenario activates the relationship between land prices and technological development in agriculture as discussed above to simulate demand-driven productivity increases.
3. Armington elasticities: GTAP simulations are typically highly sensitive to changes in the Armington elasticities. To evaluate the sensitivity, we simulate the core scenario using double core elasticities, i.e. four times the standard GTAP elasticities.
4. Elasticity of substitution between land types: We were unable to empirically estimate the elasticity of substitution between cultivable and grazable land in the livestock sectors, i.e. how freely livestock moves between the two types of land in response to changes in relative prices. In the core scenario, the parameter was arbitrarily set to 1. In this scenario, we increase the elasticity to 100 to simulate a much closer substitutability of land types in the livestock sector.[13]

# 5. Results

## Core scenario

The main purpose of this section is to demonstrate the impact of our modifications to the standard GTAP model and database, specifically our modelling of a land supply curve. To accomplish this, we compare three different closures representing different assumption with respect to land supply. As discussed above, the *Standard* GTAP closure assumes fixed land supply (vertical supply line), i.e. expansion of total land use in any region is not possible. The standard GTAP model allows for an alternative closure specifying *Perfectly Elastic* land supply (horizontal supply line). This is the opposite extreme, where land is assumed to be abundant in all regions, such that any increase in demand for land is met at constant prices.[14] Our modification introduces the land *Supply Curve*,

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[13] Perfect substitution between land types is represented by an infinitely high elasticity of substitution. Setting the elasticity to 100 is a reasonable approximation.

[14] On a more technical note: The Perfectly Elastic land supply closure is constructed by making the land supply price exogenous and land supply endogenous (i.e. swapping the two variables) and making land supply perfectly mobile (rather than sluggish) between sectors. It makes no sense to limit the movement of land between sectors, when land is assumed to be freely available for any use.

representing a generalisation of the two extremes determined by the empirical potential for land use expansion in each region.

We shock US household demand for wheat by 500.000 tonnes and report results in terms of changes in wheat production and changes in total land use across regions. In other words, we ask from *where* the extra wheat is obtained and *how* it is produced.[15]

**Figure 7: Change in wheat production, comparing different closures**

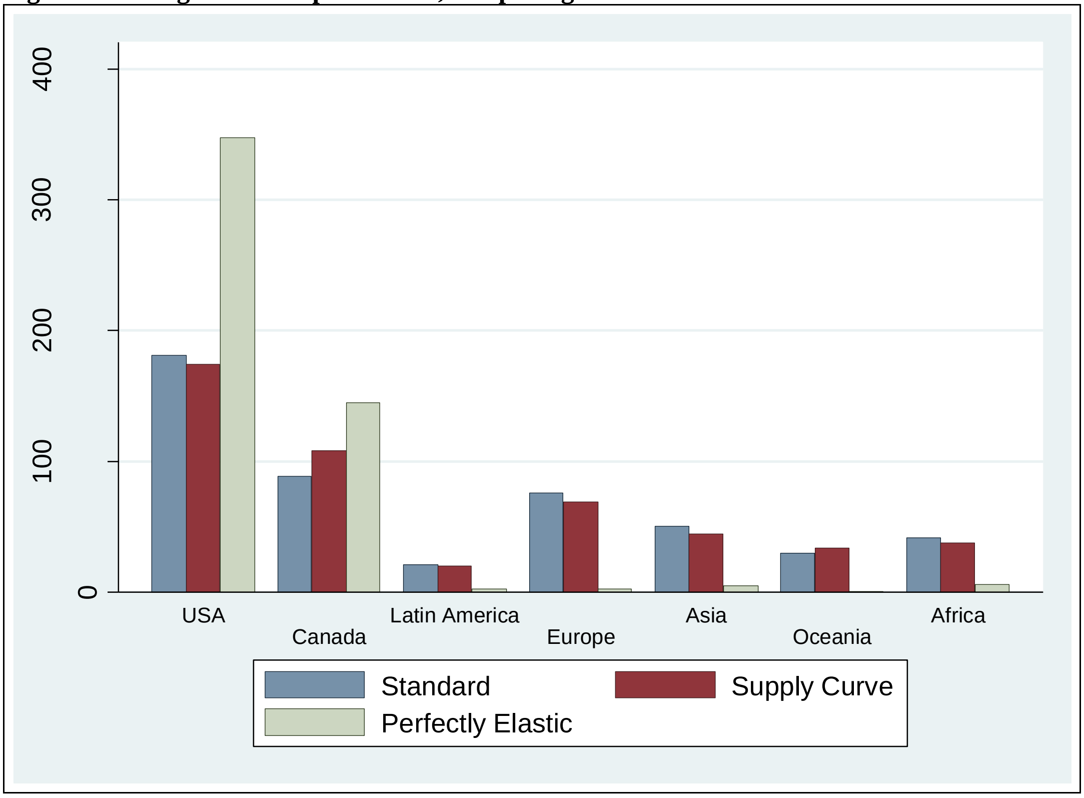

Figure 7 presents the change in wheat production in different regions of the world caused by an increase in US household wheat demand by 500.000 tonnes, comparing the three possible closures, Standard (fixed land supply), Supply curve (our modification) and Perfectly elastic land supply. Small differences exist between the Standard and the Supply Curve closures, but the overall pattern remains more or less the same. Most of the extra demand is met by domestic and Canadian supply, but the other regions also supply significant quantities. In contrast, the closure with perfectly elastic land supply places virtually the entire production expansion in North America.

Consider first the Standard and the Supply Curve closures. The pattern of production changes is largely determined by prevailing trade patterns. These trade patterns reflect the relative marginal costs of supplying wheat to US households, when accounting for production costs, transport costs, tariffs and other international trade barriers. Most of the US' household wheat demand is supplied domestically, with sizeable portions imported from Canada. The largest part of the increase in demand is therefore met by expansions in production in these two regions. Similarly, the USA and

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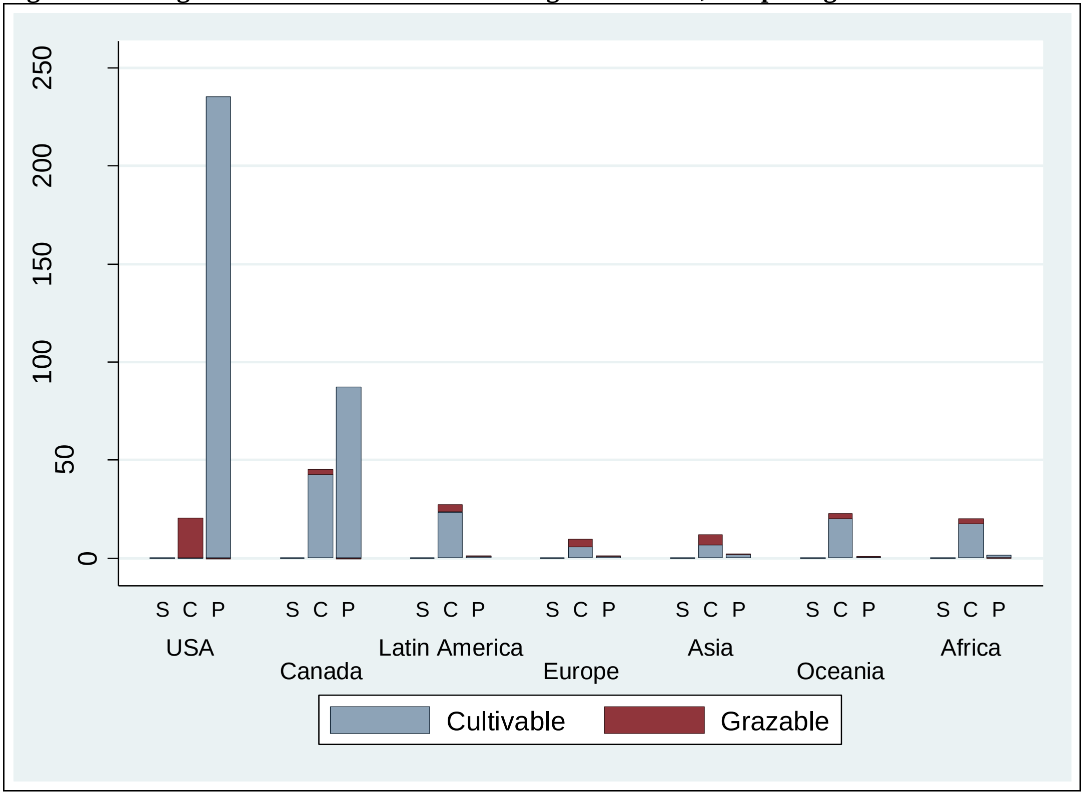
[15] The core scenario in this paper (the supply curve closure) is identical to the core USA scenario discussed in Kløverpris et al. (submitted). The results are presented in slightly different ways, using different country groupings. Otherwise the results are identical.

Canada both export large quantities of wheat to the rest of the world. As US exports decline to meet the domestic demand, the supply shortfall on the export markets are covered by output expansions in the rest of the world. The more detailed results (not shown in figure 7) reveal an interesting example of indirect trade effects: Both the USA and Europe supplies significant quantities of wheat to the Middle East and North Africa (included in the Africa region in figure 7). When wheat from the USA declines, wheat production in Europe expands, not only to cover its own supply shortfall, but also the needs of the Middle East and North Africa region. Thus, the relatively large impact on European wheat production reflects indirect trade links with third countries as well as direct trade relationships with the USA.

It may seem surprising that the land supply closure (short of perfectly elastic land supply) plays such a relatively small role. After all, we would expect that crop cultivation would be greatly affected by the potential for land use expansion. The potential for land use expansion does affect the relative marginal costs of supply from different regions, but the impact is relatively minor. Comparing the supply curve closure with the standard closure, we see that allowing for increased land supply actually reduces the production of wheat in the USA and some of the other regions. The reason is that these regions are relatively land scarce compared to Canada that utilises a smaller proportion of its land potential (see table 3 above). Therefore, it is cheaper to produce more wheat in Canada by expanding the total area of cultivation. Thus, taking land supply expansions into account changes the patterns of supply response, but only marginally. Although the variations in land scarcity across regions are significant, land rents represent a small share of total costs (in most regions less than 20 percent), and only a minor part of the land price increases are transmitted through to the market prices of crops.

Moving to the other extreme and assuming that land supply is perfectly elastic generates a much larger supply response in the USA and Canada and virtually none in the rest of the world. Facing no land constraints, it is cheaper to produce the extra wheat close to the market, and there is less need to spread the demand towards more distant suppliers.

**Figure 8: Changes in total use of cultivable and grazable land, comparing different closures**



Note: 'S' = Standard Closure; 'C' = Supply Curve closure; 'P' = Perfectly Elastic closure

Whereas figure 7 shows where production increases to satisfy the extra demand, figure 8 reveals how the output is generated. The bars represent the expansion in the use of cultivable and grazable land in each region, comparing the three different closures, Standard GTAP (the 'S' column), the Supply Curve (the 'C' column) and the Perfectly Elastic (the 'P' column). It should not come as a surprise that the standard GTAP closure predicts no change in agricultural land use – this is exactly the defining characteristic of this closure. More interesting are the other two closures.

The supply curve closure shows an expansion in agricultural land use in all regions, particularly in Canada. Latin America, Oceania (basically Australia) and Africa also experience significant land use expansions compared to their modest increases in wheat output. In contrast, the US land expansion is fairly small. This pattern reflects two results. Firstly, much land for wheat production in the USA is obtained by displacing the cultivation of other crops. This generates a shortfall of US supply of non-wheat crops, which spreads across the world market through increased imports and reduced exports. Thus, the expansion of land use in Latin America, Oceania and Africa is not only designated for cultivation of wheat, but also for production of other crops to make up for some of the global supply shortfall caused by US displacement. Secondly, the US wheat production increase is based on relatively intensive practices, whereas wheat production in Latin America, Oceania and Africa is more extensive, reflecting differences in unused land availability. All the US land use expansion takes place on grazable land due to the full utilisation of cultivable land. According to our definition, wheat cannot be cultivated on grazable land, so the expansion is generated by a displacement of livestock from cultivable land onto grazable land.

The closure incorporating Perfectly Elastic land supply assumes that land (of both types) is freely available at constant prices. Compared with the supply curve closure, the wheat demand increase generates a much larger expansion in US and Canadian land use, but almost no expansion in most of the other regions. Since land is freely available at constant costs, extensive use of land is the cheapest way to expand wheat cultivation.

### *Reality check*

The modifications made to the GTAP model involve distinguishing between land measured in physical units and the productive capacity of land. As discussed in section 2 above, changing land use from a specialisation in the cultivation of a single (or few) crops to a more equal allocation across all sectors may increase the productive capacity of land and thereby raised average agricultural yields per hectare. Thus, when discussing results, it is instructive to evaluate whether changes in yields are within reasonable levels. In the core scenario, wheat yields in the USA increase by around 0.06 percent, well within plausible limits. Interestingly, the adjustment factor introduced in section 2, *PSF(i,j,r)*, decline slightly by about -0.008 percent. This suggests that the small yield increase is not caused by reallocations of land between sectors, but rather by other factors, such as the application for more inputs (labour, capital and intermediate inputs) per hectare.

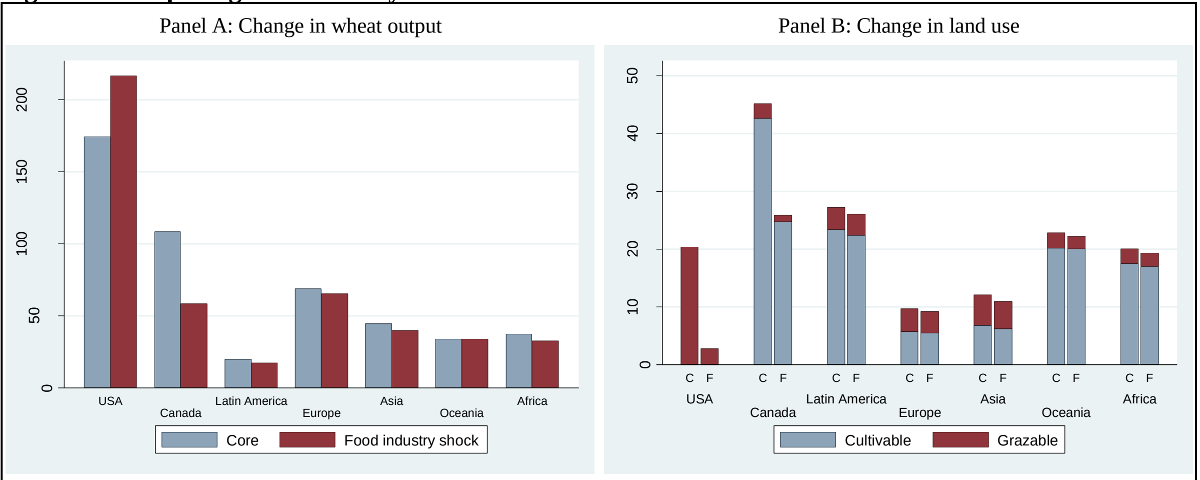
## *'Sensitivity' scenarios results and interpretations*

The core scenario applies a particular set of assumptions to demonstrate the value of employing an empirically based land supply curve in policy simulations. To qualify the discussion a bit more, we show how the results vary when we alter some of these assumptions. In all graphs below, the 'Core' scenario reproduces the 'Supply Curve' closure in the graphs above.

### *Food industry shock scenario*

The core scenario places the demand shock with private households in order to generate as 'neutral' a shock as possible. But this is not necessarily the most appropriate way to model increasing demand. Figure 9 show the impact of placing the same increase in demand (500.000 tonnes of wheat) in the food industry instead.

**Figure 9: Comparing food industry shock with core scenario**



Note: 'C' = core scenario; 'F' = Food industry shock scenario

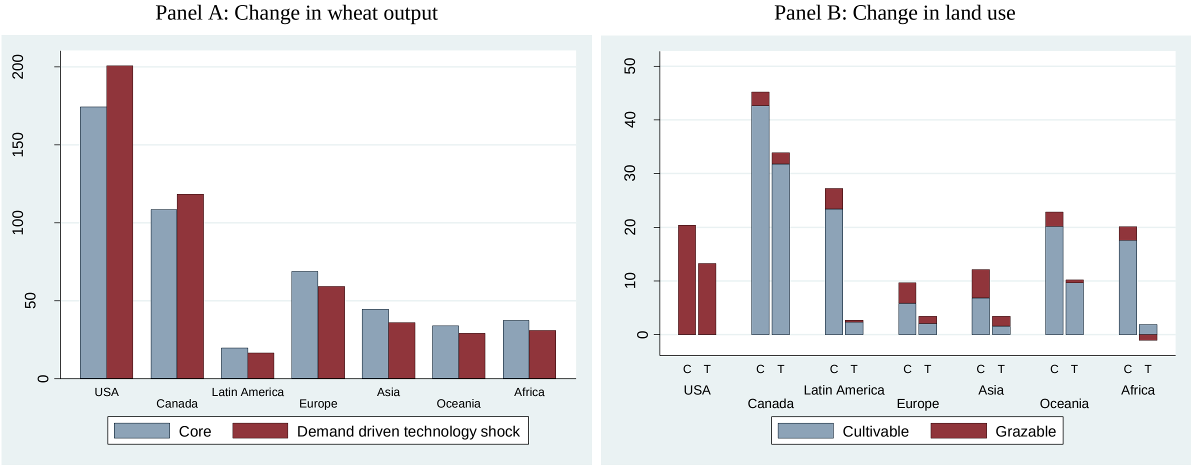
Placing the demand shock in the food industry instead of with the private households generates a larger output increase in the USA and a smaller increase in Canada (panel A). As in the core scenario, this largely reflects existing trade patterns. Whereas private households obtain a significant share of their wheat purchases (around 40 percent) from abroad (mainly Canada), the food industry is much more dependent upon domestic supply (around 11 percent import share). A more surprising result is the smaller expansion in US agricultural land use despite a larger wheat production increase (panel B). This apparent paradox is actually a consequence of the way we model the demand shocks. The shock produces a shift in demand from other products towards wheat, while satisfying the budget constraints of the households or food industry. This actually implies a decline in the demand for other products than wheat. Agricultural and food products comprise a relatively small share of the national private households' consumption basket, so in the core scenario this drop in demand is spread across the entire economy and is barely noticeable in the agricultural sector. However, input demand by the food industry is more concentrated on agricultural products, and other agricultural sectors than wheat therefore face a relatively large fall in demand reducing the need to expand the agricultural land area.

The food industry scenario demonstrates the difficulty of specifying a 'neutral' demand shock in a general equilibrium model. Results vary across experiments depending on where the demand shock is placed and how it is implemented into the model. This emphasises the value of carefully tailoring the model to represent the needs of each particular analysis.

### *Demand-driven technology scenario*

In this scenario, we activate the demand-driven technological development mechanism discussed above, specifying that 1 percent increase in the price of land induces a 0.5 percent increase in the productivity of land. Results are presented in figure 10.

**Figure 10: Comparing demand-driven technology with core scenario**



Note: 'C' = core scenario; 'T' = technology scenario

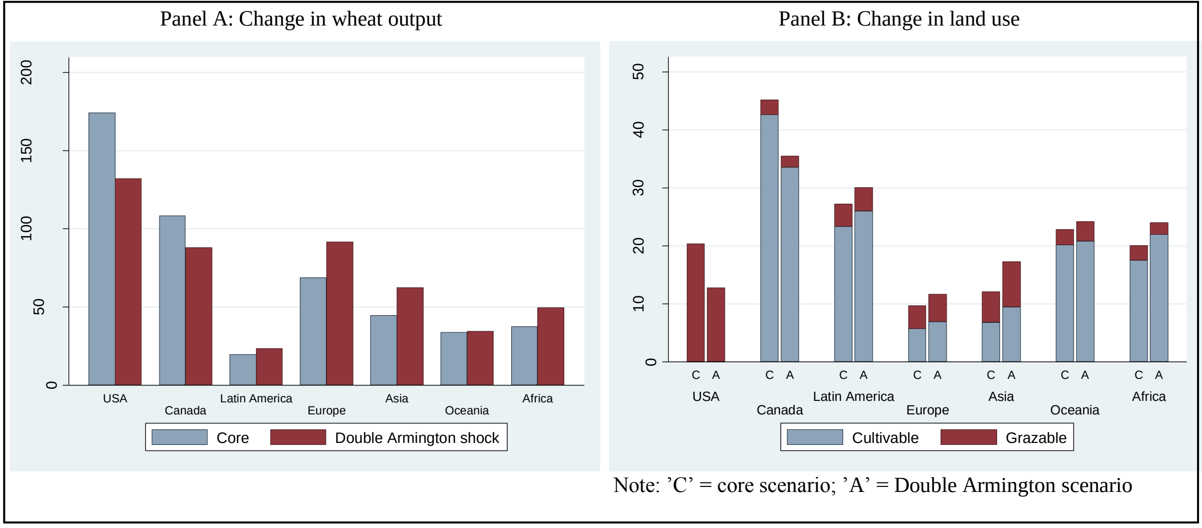
The demand-driven technological development does not significantly change the pattern of where the extra wheat is produced (panel A). The North American countries produce a little more, the rest of the world a little less. However, it does change the consequences of the demand shock in terms of land use (panel B). The increase in wheat demand generates a pressure on land resources, raises land prices and induces land specific technological development. The improvements in land productivity produce higher yields and reduce some of the pressure on land, resulting in a smaller expansion of land use.

The difference in land use change between the two scenarios is largest in Latin America, Oceania and Africa. This is actually more an indirect consequence of technological development in the USA and Canada than a direct effect of local progress. With improved land productivity, US farmers manage to produce greater quantities of wheat without reducing production of other crops to any large extent.[16] Compared with the core scenario, there is very little shortfall in the supply of non-wheat crops on the world market, greatly reducing the need for expansions of agricultural land area in Latin America, Oceania and Africa. Thus, indirectly US productivity improvements may reduce pressures on land in other parts of the world.

### *Double Armington scenario*

Increasing the Armington elasticities makes international trade more responsive to changes in relative prices. To evaluate this sensitivity, we simulate a scenario assuming double Armington elasticities compared to the core scenario (i.e. four times the standard GTAP Armingtons). Results are presented in figure 11.

**Figure 11: Comparing Double Armington with the core scenario**



Note: 'C' = core scenario; 'A' = Double Armington scenario

Doubling the Armington elasticities generates a distinctive pattern showing a smaller wheat output increase in USA and Canada and corresponding larger increase in output in the rest of the world. Just as the results of the core scenario is largely determined by existing trade patterns, increasing the Armington elasticities reduces the influence of the trade patterns. The output expansions are spread more evenly across the globe, with the largest increases generated by the most important wheat producers, Europe and Asia. A similar pattern can be seen for land use changes.

### *Near perfect substitution between land types*

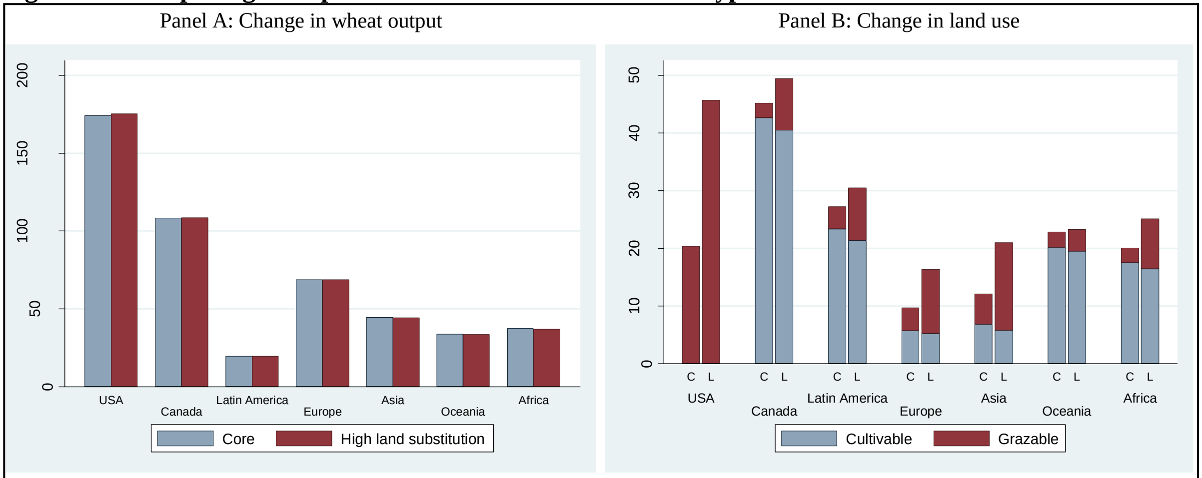
The sub-division of land into two types introduces a new parameter, the elasticity of substitution between cultivable and grazable land. It governs the ease with which livestock sectors release cultivable land for crop cultivation in return for expansion on grazable land. We have no empirical

---

[16] This is partly due to our way of modelling demand-driven technological development. We assume that the productivity improvements are linked to the soil, such that all crop sectors benefit equally from the development. Thus not only wheat, but also other crops, benefit from the development. An alternative way is to make the technological development sector specific such that productivity improvements are largest in sectors with the greatest increase in demand for land. This would result in a larger productivity increase in the wheat sector and a smaller improvement in non-wheat crops. This alternative is not pursued further in this paper.

estimates of the parameter, so in the core scenario we chose arbitrarily the value 1. In this sensitivity scenario, we increase the elasticity to 100, approximating perfect substitution between land types. This is not particularly realistic, but it demonstrates the impacts of moving to the extreme. Results are presented in figure 12.

**Figure 12: Comparing near perfect substitution between land types with the core scenario**



Panel A: Change in wheat output

Panel B: Change in land use

Note: 'C' = core scenario; 'L' = Land substitution scenario

The results indicate that the wheat supply responses are very robust to variations in the value of elasticity of substitution between land types (panel A). The changes in output in all regions are almost exactly the same in both scenarios. On the other hand, the changes in land use are greatly affected by the value of the elasticity (panel B). The greater substitutability between land types increases the expansion on grazable land. To the extent that livestock sectors occupy cultivable land, displacement of livestock from cultivable land onto grazable land can be seen as a valve relieving some of the pressure on land caused by the increasing demand for wheat. When the two types of land are (near) perfect substitutes, this displacement mechanism is much smoother. The difference in the two scenarios is particularly large in USA, Europe and Asia, where the area of cultivable land is almost completely utilised (land expansion is costly) and grazable land is relatively abundant (land expansion is cheap).

# 6. Discussion

Our overall finding from the core scenario and the sensitivity simulations is that the global supply responses are largely determined by the prevailing trade patterns reflecting the relative costs for different regions of supplying the US market with wheat, when taking into account production costs, transport costs, tariffs and other barriers to trade. Notably, the differences between the standard GTAP land supply closure (assuming fixed land supply) and our modified closure (assuming land supply determined by expansion potential) are small. This result suggests that the standard GTAP closure is a reasonable approximation in analyses that do not focus specifically on land use changes. Allowing agricultural land to expand in regions with abundant land resources does affect the relative costs of supplying agricultural commodities, but the impact is small compared to other factors, such as international trade barriers.

On the other hand, in GTAP analyses with a particular emphasis on land use changes, such as agricultural policy analyses and Life-Cycle Assessment (LCA) of agricultural commodities, the improvements to the land supply specification introduced in this paper are crucial. The standard

GTAP closure rules out expansion in the agricultural land area, thus ignoring important environmental impacts and making results seem implausible and less credible. Our land supply closure yields direct estimates of the land use consequences of policy scenarios based on empirical evidence of the potential for expansion of the agricultural land area.

One of the main advantages of the modifications is their simplicity (the GTAP code is given in Appendix A). Given the extra data on land use and expansion potential required for calibration of the parameters, the extended land supply specification is very easy to implement. Furthermore, the general approach can be extended to other primary factors in fixed supply, such as skilled and unskilled labour, utilising data on unemployment rates to generate the labour supply curves.

Similarly, though our proposed solution to the common problem of incomplete market clearing of land measured in hectares is merely an approximation to a theoretically founded land market, it has three major advantages: 1) it is very easy to implement, with crop specific measures of land use (publicly available from FAOSTAT) as the only data requirement; 2) it can be characterised as an independent add-on, which does not interfere with the solving of the standard model variables – as such the extension does not introduce new problems of model conversion[17]; and 3) it is possible to provide an interpretation of the discrepancy between the standard GTAP land market clearing and this extension.

However, there is still room for further improvements. We have identified three such areas:

- ***Intensification of cultivation:*** There are essentially two ways, in which the global agriculture may increase production: by expanding the agricultural land area or by intensifying production (producing more per hectare of land). We have not discussed the issue of intensification in any detail this paper (interested readers are referred to Kløverpris et al. (submitted)), mainly because a more realistic modelling of agricultural intensification has not been a part of the modifications. There is, however, room for improvement in this area. In the GTAP model intensification is modelled as a substitution of labour and capital for land (as illustrated in the production structure in figure 1 above), yielding a higher output per hectare. This general production structure is common for all GTAP economic sectors and does not take into consideration any physical and legal limitations to intensification. For instance, Denmark has imposed very strict limitations on the use of fertilisers in agriculture for environmental reasons. A valuable contribution would be to implement such restrictions in the model.
- ***Potential grazable land:*** As mentioned in section 3 on the modification of the database, we were unable to find reliable data on the potential grazable land areas, and we had to approximate it ourselves, possibly overestimating the availability of grazable land. Empirical data in this area would improve the database.
- ***Alternative to 'sluggishness' of land:*** The 'no-land-market-clearing-in-hectares' inconsistency in standard GTAP is essentially related to the 'sluggishness' assumption. We have provided a simple practical solution, but to solve the problem once and for all would probably require an alternative specification. We believe that the introduction of Agricultural Ecological Zones (AEZs) by Lee et al. (2005) is a significant step in the right direction. The primary argument for specifying land as sluggish was to prevent implausible

---

[17] Our earlier attempts to solve the problem were more invasive and introduced conversion problems, i.e. the model failed to converged to a general equilibrium. In more technical terms, the diagnostic variable *Walraslack,* which is supposed to equal zero in a general equilibrium, failed this test. With the solution introduced in this paper, no such problems were encountered – in all simulations *walraslack* was equal to zero (at the 6th decimal place).

land use changes, such as e.g. massive conversion of wheat land to cultivation of rice. With the introduction of AEZs, such land conversion may only take place within the same AEZ. Further work is still needed, in particular with combining the AEZ-approach with the van Meijl land supply curves used in this paper, such that a land supply curve is specified for each AEZ. This would require estimation of AEZ- and country-specific potential for land expansion, among other things.

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# Appendix A: Modifications to the standard GTAP code

This appendix details the modifications made to the standard GTAP model. It is intended for users of the GTAP model, who may be interested in using (or checking) some of our code modifications. Basic knowledge of GTAP coding is presumed.

## *Modelling the subdivision of land*

We define new sets to distinguish between land and non-land endowments. Land endowments define the two sub-types of land, cult(ivable) and graz(able):

```
!   Defining sets for new land endowment nest    !

Set
    LND_ENDW # Land endowments # (Cult, Graz);
Subset
    LND_ENDW is subset of ENDW_COMM;
Set
    NLND_ENDW # Non-land endowments # = ENDW_COMM - LND_ENDW;
```

We modify the existing endowment-demand equation so that it only works for non-land endowments (modifications highlighted by bold+italics):

```
!   Equation changed so that it only ranges over non-land endowments !
Equation ENDWDEMAND
# demands for endowment commodities (HT 34) #
(all,i,NLND_ENDW)(all,j,PROD_COMM)(all,r,REG)
    qfe(i,j,r)
        = - afe(i,j,r) + qva(j,r)
        - ESUBVA(j) * [pfe(i,j,r) - afe(i,j,r) - pva(j,r)];
```

We define new quantity and price variables for the land endowment composites:

```
Variable (all,j,PROD_COMM)(all,r,REG)
    qle (j,r) # Demand for land endowment composite #;
Variable (all,j,PROD_COMM)(all,r,REG)
    ple (j,r) # Price of land endowment composite #;
```

The definition of the elasticity of substitution between the two types of land, arbitrarily set equal to 1:

```
Coefficient (parameter)
    ESUBLE # Elast. of subst. between land endowments #;
read
    ESUBLE from file GTAPPARM header "ESBL";
```

Defining demand for the land composite similarly to the existing endowment demand equation. We have ignored technological development variables in this nest:

```
Equation LNDCOMP
#   demand for land endowment composite #
(all,j,PROD_COMM)(all,r,REG)
    qle(j,r)
        = qva(j,r) - ESUBVA(j) * [ple(j,r) - pva(j,r)];
```

Defining the price of the land composite:

```
!   If an industry does not use land at all, the price of the land
    composite is the simple average of land prices. The price doesnt really
    matter  !
Zerodivide default 0.5;

Coefficient (all,i,LND_ENDW)(all,j,PROD_COMM)(all,r,REG)
    SLC(i,j,r) # share of land type i in land composite #;
Formula (all,i,LND_ENDW)(all,j,PROD_COMM)(all,r,REG)
    SLC(i,j,r) = VFA(i,j,r) / sum(k,LND_ENDW,VFA(k,j,r));

zerodivide off;

Equation LNDPRICE
# Price of land endowment composite #
(all,j,PROD_COMM)(all,r,REG)
    ple(j,r)
        = sum(k,LND_ENDW, SLC(k,j,r) * [pfe(k,j,r) - afe(k,j,r)]);
```

Defining demand for each type of land given demand for the land composite:

```
Equation LNDDEMAND
# Demand for different land types given land endowment composite #
(all,i,LND_ENDW)(all,j,PROD_COMM)(all,r,REG)
    qfe(i,j,r)
        = - afe(i,j,r) + qle(j,r)
        - ESUBLE * [pfe(i,j,r) - afe(i,j,r) - ple(j,r)];
```

### *Modelling the land supply curve*

By multiplying the numerator and the denominator in equation (4) with the market price, we can write the land supply elasticity in value form:

$$\varepsilon \;\; i,r = \frac{VPL(i,r) - VOM(i,r)}{VPL(i,r)} \tag{16}$$

where *VPL(i,r)* is a new coefficient representing the value of potentially available land of type *i* in region *r*. We have calculated the coefficient as

$$VPL(i,r) = \frac{VOM(i,r)}{u(i,r)} \tag{17}$$

where

$$u(i,r) = \frac{QO(i,r)}{a(i,r)} \tag{18}$$

is the land utilisation ratio presented in table 3. By using utilisation ratios to merge the new data into the GTAP database, we avoid risk of mismatch between different data sources. We added the coefficient VPL(i,r) to our baseline data and read it into the model with:

```
Coefficient(all,i,LND_ENDW)(all,r,REG)
    VPL(i,r) # Value of potential suitable cropland #;
Read
    VPL from file GTAPDATA header "VPL";
Update (all,i,LND_ENDW)(all,r,REG)
    VPL(i,r) = pm(i,r);
```

The land supply elasticity is defined as in (17):

```
Coefficient (all,i,LND_ENDW)(all,r,REG)
    ELND(i,r) # Elasticity of supply of crop land #;
Formula (all,i,LND_ENDW)(all,r,REG)
    ELND(i,r) = [VPL(i,r) - VOM(i,r)]/VOM(i,r);
```

We define a swap-variable to make it easier to activate or deactivate the land supply curve in the command file:

```
Variable (all,i,LND_ENDW)(all,r,REG)
    landsupply(i,r) # Land supply curve swap-variable #;
```

The land supply curve is given by (3) and is activated by swapping *landsupply(i,r)* with *qo(i,r)*. The deflation of the land market price with *pfactwld* ensures that the model satisfies the homogeneity condition.

```
Equation CROP_SUPPLY
# Land supply curve #
(all,i,LND_ENDW)(all,r,REG)
      landsupply(i,r) = ELND(i,r)*[pm(i,r) - pfactwld] - qo(i,r);
```

### Modelling land market clearing in physical units

To model land market clearing in physical units (hectares), we need to add information on the current land use pattern measured in (1,000) hectares. The section on modifications to the GTAP database describes our estimation of total cultivable and grazable land area in use based on data from Ramankutty et al. (2007). However, this database does not obtain the distribution of cropland and pasture across sectors. To estimate this distribution, we retrieve data on harvested area from the FAOSTAT database for 146 primary crops in more than 200 countries aggregated into GTAP concordance. The resulting database, listing the share of total land in each region devoted to the cultivation of each crop, is multiplied with our data on total cultivable land to obtain consistent data on sectoral land use. Similar data on the distribution of grazable land across land using livestock sectors (ctl and rmk) were not available, so we applied the (land rent) distribution from our modified GTAP database. Data on land use measure in physical hectares is read into the model.

```
!   Add-on: Reinterpretation of land and creation of land market clearing   !

Coefficient (all,i,LND_ENDW)(all,j,PROD_COMM)(all,r,REG)
    LND(i,j,r) # physical land used in sector j #;
Read LND from file GTAPDATA header "QLND";

Variable (orig_level=LND)(all,i,LND_ENDW)(all,j,PROD_COMM)(all,r,REG)
    ldm(i,j,r) # Quantity of physical land (ha) type i in sector j #;

Update (all,i,LND_ENDW)(all,j,PROD_COMM)(all,r,REG)
    LND(i,j,r) = ldm(i,j,r);
```

We define the productivity scaling factor

```
Variable (all,i,LND_ENDW)(all,r,REG)
    psf(i,r) # Productivity scaling factor of land type i #;
```

and specify the relationship between the standard GTAP expression of land and land in physical terms.

```
Equation LNDDECOMP
# Decomposition of land values into physical land and productivity scaling #
(all,i,LND_ENDW)(all,j,PROD_COMM)(all,r,REG)
    qfe(i,j,r) = psf(i,r) + ldm(i,j,r);
```

Our closure specifies that *apf(i,r)* = 0, which implies that *qo(i,r)* = *lsp(i,r)*. We insert the closure and the relationship between standard GTAP land supply and land supply in physical terms (12) into the market clearing condition.

```
Equation MKTCLLND
# Market clearing condition for physical land #
(all,i,LND_ENDW)(all,r,REG)
     sum{j,PROD_COMM,LND(i,j,r)}*qo(i,r)
            = sum{j,PROD_COMM,LND(i,j,r)*ldm(i,j,r)};
```

### Modelling household demand shock

We define two new sets, identifying the exogenous and endogenous demand shocks (in this case wheat is exogenous and all other commodities are endogenous)[18]. The exogenous shock is the shock specified by the analyst, whereas the endogenous demand shocks are the changes to demand for all other commodities necessary to ensure that the budget constraint is not violated.

```
Set
    EXOG # Products, for which demand shock is exogenous # (wht);
Subset
    EXOG is subset of TRAD_COMM;
Set
    ENDO # Products, for which demand shock is endogenous # = TRAD_COMM - EXOG;
```

We define two variables, one representing the demand shocks and one representing the endogenously calculated demand shocks.

```
Variable (all,i,TRAD_COMM)(all,r,REG)
    hh_dmdshk(i,r) # Demand shock representing preference shift #;

Variable (all,r,REG)
    hh_endodmd(r) # Common endogenous demand shock balancing the exog shk #;
```

We modify the existing equation specifying private household demand. The modification is highlighted by bold+italics:

---

[18] With this specification the designation of the exogenous and endogenous demand shocks are made in the model file. This is not very elegant as a change in the designation requires a re-compilation of the entire model file. A more practical solution would be to enable the designation to be made in a command file for each simulation. Since we have only analysed a change in demand for wheat, we have not tried to code this – however, it should be possible.

```
Equation PRIVDMNDS
# private consumption demands for composite commodities (HT 46) #
(all,i,TRAD_COMM)(all,r,REG)
    qp(i,r) - pop(r)
        = sum(k,TRAD_COMM, EP(i,k,r) * pp(k,r)) + EY(i,r) * [yp(r) - pop(r)]
        + hh_dmdshk(i,r);
```

The budget constraint requires that the budget-share weighted average of all (percentage) changes in demand is equal to zero:

```
Equation BUDGBALANCE
# Condition on all demand shocks to restore balance to the budget #
(all,r,REG)
    sum(k,TRAD_COMM, CONSHR(k,r)*hh_dmdshk(k,r)) = 0;
```

Finally, we identify the size of the endogenous demand shocks by equalising them across commodities, generating a proportional change in demand for all commodities:

```
Equation DMDSHKID
# Identifying all endogenous demand shocks #
(all,i,ENDO)(all,r,REG)
    hh_dmdshk(i,r) = hh_endodmd(r);
```

### *Modelling industry demand shock*

The industry demand shocks are specified analogously to the household demand shock, so we present it here without further comments:

```
Variable (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG)
    id_dmdshk(i,j,r) # Exogenous demand shock representing ind. input shift #;

Variable (all,j,PROD_COMM)(all,r,REG)
    id_endodmd(j,r) # Common endogenous demand shock balancing the exog shk #;

Coefficient (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG)
    COSTSHR(i,j,r) # Cost shares of ind. j expend. on intermediate inputs #;

Formula (all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG)
    COSTSHR(i,j,r) = VFA(i,j,r)/sum(k,TRAD_COMM,VFA(k,j,r));

Equation INTDEMAND
# industry demands for intermediate inputs, including cgds #
(all,i,TRAD_COMM)(all,j,PROD_COMM)(all,r,REG)
    qf(i,j,r)
        = - af(i,j,r) + qo(j,r) - ao(j,r)
        - ESUBT(j) * [pf(i,j,r) - af(i,j,r) - ps(j,r) - ao(j,r)]
        + id_dmdshk(i,j,r);

Equation COSTBALANCE
# Condition on all demand shocks to restore balance to the budget #
(all,j,PROD_COMM)(all,r,REG)
    sum(k,TRAD_COMM, COSTSHR(k,j,r)*id_dmdshk(k,j,r)) = 0;

Equation IDDMDSHKID
# Identifying all endogenous demand shocks #
(all,i,ENDO)(all,j,PROD_COMM)(all,r,REG)
    id_dmdshk(i,j,r) = id_endodmd(j,r);
```

### *Modelling endogenous technological development*

We define a technological change elasticity, which determines the strength of the relationship between change in the price of land and technological development. The parameter is arbitrarily set to 0.5:

```
Coefficient (parameter)
    TECH
    # Technological change elasticity #;
Read
    TECH from file GTAPPARM header "TECH";
```

We define a swap-variable to make it easier to activate or de-activate the endogenous technological development feature in a command file.

```
Variable (all,j,PROD_COMM)(all,r,REG)
    techchange(j,r)
    # Swap variable defining link between price and productivity shock #;
```

To make the relationship asymmetric, we need to define the levels-version of the market price of land:

```
Coefficient (all,j,NSAV_COMM)(all,r,REG)
    PM_L(j,r) # Levels-version of market prices #;
Formula (initial)(all,j,NSAV_COMM)(all,r,REG)
    PM_L(j,r) = 1.0;
Update (all,j,NSAV_COMM)(all,r,REG)
    PM_L(j,r) = pm(j,r);
```

This equation forms the link between the market price and technological development. The equation is deactivated when *techchange(j,r)* is endogenous. To activate the equation, swap *techchange(j,r)* with *afeall(j,r)*. In the beginning of the first run of every simulation, market prices are normalised at 1. If the land price is reduced below 1 in any subsequent cycle of the simulation, the equation is deactivated.

```
Equation TECHLINK
# Link between land price and productivity shock #
(all,j,PROD_COMM)(all,r,REG)
    techchange(j,r) = IF{PM_L("crop",r)>=1,TECH*[pm("crop",r) - pfactwld]}
                    - afeall("crop",j,r);
```

# Appendix B: Data on land use, potential land availability and adjustments made

This appendix presents detailed data on land use, potential land availability and adjustments made for almost all countries in the world. The utilisation rates are subsequently aggregated to GTAP concordance. The first two columns show utilisation rates on cultivable land, of crop cultivation alone and cultivation and pasture combined. The utilisation rates in the first column are in some instances greater than 100. Our data on potential cultivable land is based on a dichotomous definition of suitability for rainfed cultivation. Thus, land is either suitable or unsuitable. Utilisation rates of more than 100 percent may therefore reflect cultivation on lands only marginally suitable for crops, possibly with considerable investment in irrigation and fertilisation. In the second and third columns (merged into the GTAP database), utilisation rates are capped at 100 percent and the utilisation of grazable land is increased to simulate the ‘conversion’ of some grazable land to cultivable land.

| | Land utilisation rates | | | Share of pasture | | Adjustments (percent of total land area) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Crountry | Crops on cult. land | Crops and pasture on cult. land | Pasture on grazable land | on cultivable land | on grazable land | Desert | Steepness | Protected | Settlement on cultiv. land | Settlement on graz. land |
| Afghanistan | 58 | 100 | 85 | 42 | 58 | 20 | 21 | 0 | 0 | 1 |
| Albania | 46 | 73 | 0 | 37 | 63 | 0 | 30 | 4 | 3 | 1 |
| Algeria | 55 | 100 | 100 | 45 | 55 | 88 | 6 | 5 | 0 | 0 |
| Andorra | 0 | 100 | 100 | 0 | 100 | 0 | 0 | 0 | 0 | 0 |
| Angola | 9 | 90 | 34 | 90 | 10 | 3 | 3 | 12 | 0 | 0 |
| Argentina | 84 | 100 | 100 | 16 | 84 | 20 | 10 | 65 | 0 | 0 |
| Armenia | 42 | 100 | 46 | 58 | 42 | 0 | 35 | 10 | 0 | 4 |
| Australia | 16 | 64 | 81 | 74 | 26 | 38 | 4 | 14 | 0 | 0 |
| Austria | 92 | 100 | 55 | 8 | 92 | 0 | 20 | 28 | 3 | 1 |
| Azerbaijan | 41 | 88 | 14 | 53 | 47 | 0 | 14 | 7 | 1 | 2 |
| Bangladesh | 133 | 100 | 100 | 0 | 100 | 0 | 8 | 2 | 28 | 0 |
| Belarus | 84 | 100 | 16 | 16 | 84 | 0 | 0 | 6 | 2 | 0 |
| Belize | 15 | 21 | 0 | 28 | 72 | 0 | 9 | 54 | 0 | 0 |
| Benin | 66 | 77 | 4 | 15 | 85 | 0 | 4 | 23 | 2 | 0 |
| Bhutan | 36 | 64 | 10 | 44 | 56 | 10 | 21 | 26 | 1 | 0 |
| Bolivia | 9 | 75 | 33 | 88 | 12 | 10 | 16 | 21 | 0 | 0 |
| Bosnia and herzegovina | 43 | 86 | 3 | 50 | 50 | 0 | 24 | 1 | 2 | 0 |
| Botswana | 17 | 100 | 100 | 83 | 17 | 57 | 1 | 30 | 0 | 0 |

| | Land utilisation rates | | | Share of pasture | | Adjustments (percent of total land area) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Crountry | Crops on cult. land | Crops and pasture on cult. land | Pasture on grazable land | on cultivable land | on grazable land | Desert | Steepness | Protected | Settlement on cultiv. land | Settlement on graz. land |
| Brazil | 20 | 67 | 17 | 70 | 30 | 1 | 3 | 19 | 0 | 0 |
| Brunei darussalam | 37 | 45 | 0 | 17 | 83 | 0 | 9 | 59 | 1 | 0 |
| Bulgaria | 50 | 74 | 1 | 33 | 67 | 0 | 16 | 10 | 1 | 2 |
| Burkina faso | 50 | 86 | 21 | 42 | 58 | 0 | 4 | 15 | 0 | 1 |
| Burundi | 83 | 100 | 52 | 17 | 83 | 0 | 13 | 6 | 8 | 0 |
| Cambodia | 63 | 87 | 2 | 27 | 73 | 0 | 18 | 24 | 2 | 0 |
| Cameroon | 42 | 51 | 2 | 18 | 82 | 0 | 4 | 9 | 1 | 0 |
| Canada | 59 | 70 | 2 | 17 | 83 | 0 | 11 | 7 | 0 | 0 |
| Central african republic | 11 | 30 | 1 | 62 | 38 | 0 | 3 | 16 | 0 | 0 |
| Chad | 15 | 94 | 55 | 84 | 16 | 38 | 3 | 9 | 0 | 0 |
| Chile | 36 | 100 | 44 | 64 | 36 | 31 | 32 | 19 | 0 | 0 |
| China | 63 | 100 | 100 | 37 | 63 | 30 | 21 | 15 | 1 | 3 |
| Colombia | 12 | 100 | 20 | 88 | 12 | 0 | 10 | 33 | 1 | 0 |
| Congo | 8 | 29 | 2 | 72 | 28 | 0 | 0 | 14 | 0 | 0 |
| Congo (democratic rep.) | 13 | 33 | 3 | 59 | 41 | 0 | 2 | 8 | 1 | 0 |
| Costa rica | 33 | 100 | 100 | 67 | 33 | 0 | 17 | 34 | 2 | 0 |
| Croatia | 46 | 85 | 19 | 46 | 54 | 0 | 8 | 10 | 2 | 0 |
| Cuba | 73 | 100 | 98 | 27 | 73 | 0 | 6 | 27 | 3 | 0 |
| Czech republic | 122 | 100 | 59 | 0 | 100 | 0 | 20 | 16 | 4 | 0 |
| Côte d'ivoire | 63 | 100 | 47 | 37 | 63 | 0 | 3 | 17 | 2 | 0 |
| Denmark | 111 | 100 | 31 | 0 | 100 | 0 | 0 | 14 | 3 | 0 |
| Djibouti | 14 | 100 | 100 | 86 | 14 | 99 | 2 | 56 | 0 | 0 |
| Dominican republic | 87 | 100 | 100 | 13 | 87 | 0 | 19 | 42 | 6 | 0 |
| Ecuador | 101 | 100 | 100 | 0 | 100 | 2 | 21 | 74 | 1 | 1 |
| Egypt | 92 | 100 | 100 | 8 | 92 | 100 | 8 | 9 | 0 | 0 |
| El salvador | 80 | 100 | 100 | 20 | 80 | 0 | 28 | 1 | 9 | 0 |
| Equatorial guinea | 31 | 38 | 0 | 19 | 81 | 0 | 3 | 21 | 1 | 0 |
| Eritrea | 68 | 100 | 100 | 32 | 68 | 42 | 0 | 4 | 0 | 1 |
| Estonia | 110 | 100 | 14 | 0 | 100 | 0 | 0 | 48 | 0 | 0 |

| Crountry | Land utilisation rates |  |  | Share of pasture |  | Adjustments (percent of total land area) |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  | Crops on cult. land | Crops and pasture on cult. land | Pasture on grazable land | on cultivable land | on grazable land | Desert | Steepness | Protected | Settlement on cultiv. land | Settlement on graz. land |
| Ethiopia | 34 | 68 | 37 | 49 | 51 | 10 | 30 | 17 | 1 | 1 |
| Finland | 76 | 77 | 0 | 1 | 99 | 0 | 2 | 9 | 0 | 0 |
| France | 62 | 91 | 14 | 32 | 68 | 0 | 7 | 13 | 4 | 0 |
| French guiana | 1 | 1 | 0 | 44 | 56 | 0 | 0 | 6 | 0 | 0 |
| Gabon | 4 | 8 | 0 | 49 | 51 | 0 | 4 | 15 | 0 | 0 |
| Gambia | 59 | 100 | 58 | 41 | 59 | 0 | 1 | 5 | 1 | 2 |
| Georgia | 36 | 76 | 38 | 53 | 47 | 0 | 32 | 4 | 1 | 1 |
| Germany | 107 | 100 | 57 | 0 | 100 | 0 | 2 | 31 | 7 | 0 |
| Ghana | 77 | 100 | 63 | 23 | 77 | 0 | 4 | 15 | 3 | 0 |
| Greece | 33 | 47 | 4 | 31 | 69 | 0 | 15 | 5 | 2 | 0 |
| Guatemala | 50 | 100 | 24 | 50 | 50 | 0 | 22 | 33 | 3 | 0 |
| Guinea | 14 | 51 | 9 | 73 | 27 | 0 | 10 | 7 | 1 | 0 |
| Guinea-bissau | 33 | 92 | 19 | 64 | 36 | 0 | 10 | 3 | 0 | 1 |
| Guyana | 4 | 14 | 1 | 67 | 33 | 0 | 10 | 2 | 0 | 0 |
| Haiti | 61 | 93 | 0 | 35 | 65 | 0 | 24 | 0 | 7 | 0 |
| Honduras | 35 | 70 | 0 | 50 | 50 | 0 | 25 | 27 | 2 | 0 |
| Hong kong | 0 | 100 | 100 | 0 | 100 | 0 | 0 | 0 | 0 | 0 |
| Hungary | 65 | 79 | 2 | 18 | 82 | 0 | 3 | 9 | 3 | 0 |
| Iceland | 0 | 0 | 0 |  |  | 0 | 22 | 9 | 0 | 0 |
| India | 92 | 96 | 6 | 5 | 95 | 2 | 8 | 5 | 3 | 8 |
| Indonesia | 120 | 100 | 17 | 0 | 100 | 0 | 24 | 24 | 4 | 0 |
| Iran | 62 | 100 | 100 | 38 | 62 | 39 | 19 | 7 | 0 | 1 |
| Iraq | 44 | 62 | 41 | 29 | 71 | 67 | 7 | 0 | 0 | 1 |
| Ireland | 47 | 100 | 51 | 53 | 47 | 0 | 1 | 1 | 2 | 0 |
| Israel | 73 | 91 | 29 | 20 | 80 | 26 | 11 | 20 | 0 | 8 |
| Italy | 69 | 95 | 17 | 27 | 73 | 0 | 24 | 19 | 6 | 0 |
| Japan | 35 | 39 | 0 | 10 | 90 | 0 | 24 | 17 | 10 | 0 |
| Jordan | 81 | 97 | 47 | 16 | 84 | 68 | 13 | 11 | 0 | 1 |
| Kazakstan | 14 | 94 | 62 | 85 | 15 | 0 | 3 | 3 | 0 | 0 |

|  | Land utilisation rates |  |  | Share of pasture |  | Adjustments (percent of total land area) |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
| Crountry | Crops on cult. land | Crops and pasture on cult. land | Pasture on grazable land | on cultivable land | on grazable land | Desert | Steepness | Protected | Settlement on cultiv. land | Settlement on graz. land |
| Kenya | 32 | 87 | 57 | 63 | 37 | 11 | 13 | 13 | 1 | 0 |
| Korea | 77 | 79 | 0 | 2 | 98 | 0 | 41 | 7 | 16 | 0 |
| Korea, dem. people's rep | 48 | 53 | 1 | 9 | 91 | 0 | 24 | 3 | 6 | 1 |
| Kuwait | 48 | 100 | 100 | 52 | 48 | 100 | 5 | 3 | 0 | 0 |
| Kyrgyzstan | 31 | 100 | 83 | 69 | 31 | 9 | 28 | 4 | 0 | 1 |
| Lao people's democratic | 28 | 50 | 0 | 44 | 56 | 0 | 54 | 16 | 1 | 0 |
| Latvia | 93 | 100 | 14 | 7 | 93 | 0 | 0 | 16 | 1 | 0 |
| Lebanon | 32 | 34 | 0 | 4 | 96 | 0 | 4 | 1 | 6 | 6 |
| Lesotho | 26 | 100 | 100 | 74 | 26 | 2 | 27 | 0 | 2 | 0 |
| Liberia | 14 | 14 | 0 | 0 | 100 | 0 | 6 | 14 | 1 | 0 |
| Libyan arab jamahiriya | 25 | 59 | 100 | 59 | 41 | 95 | 4 | 0 | 0 | 0 |
| Lithuania | 103 | 100 | 24 | 0 | 100 | 0 | 0 | 11 | 1 | 0 |
| Macedonia | 67 | 100 | 59 | 33 | 67 | 0 | 32 | 7 | 0 | 2 |
| Madagascar | 14 | 83 | 17 | 83 | 17 | 4 | 8 | 3 | 1 | 0 |
| Malawi | 28 | 72 | 7 | 61 | 39 | 0 | 20 | 16 | 0 | 3 |
| Malaysia | 108 | 100 | 7 | 0 | 100 | 0 | 24 | 26 | 2 | 0 |
| Mali | 24 | 80 | 51 | 70 | 30 | 51 | 5 | 2 | 0 | 0 |
| Mauritania | 46 | 71 | 48 | 35 | 65 | 78 | 4 | 2 | 0 | 0 |
| Mexico | 42 | 84 | 100 | 49 | 51 | 33 | 19 | 9 | 1 | 1 |
| Moldova, rep.of | 68 | 81 | 13 | 15 | 85 | 0 | 0 | 1 | 1 | 3 |
| Mongolia | 20 | 100 | 100 | 80 | 20 | 47 | 13 | 14 | 0 | 0 |
| Morocco | 71 | 100 | 100 | 29 | 71 | 34 | 21 | 1 | 0 | 2 |
| Mozambique | 14 | 99 | 50 | 86 | 14 | 5 | 7 | 7 | 0 | 0 |
| Myanmar | 49 | 53 | 0 | 6 | 94 | 0 | 35 | 6 | 2 | 0 |
| Namibia | 18 | 100 | 100 | 82 | 18 | 58 | 7 | 15 | 0 | 0 |
| Nepal | 67 | 87 | 12 | 23 | 77 | 16 | 20 | 18 | 3 | 2 |
| Netherlands | 85 | 100 | 78 | 15 | 85 | 0 | 0 | 19 | 16 | 0 |
| New zealand | 19 | 100 | 100 | 81 | 19 | 0 | 45 | 32 | 0 | 0 |
| Nicaragua | 55 | 100 | 95 | 45 | 55 | 0 | 13 | 23 | 1 | 0 |

| | Land utilisation rates | | | Share of pasture | | Adjustments (percent of total land area) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Crountry | Crops on cult. land | Crops and pasture on cult. land | Pasture on grazable land | on cultivable land | on grazable land | Desert | Steepness | Protected | Settlement on cultiv. land | Settlement on graz. land |
| Niger | 77 | 96 | 48 | 19 | 81 | 53 | 5 | 7 | 0 | 0 |
| Nigeria | 84 | 100 | 32 | 16 | 84 | 0 | 6 | 7 | 3 | 1 |
| Norway | 73 | 78 | 0 | 6 | 94 | 0 | 9 | 5 | 0 | 0 |
| Oman | 26 | 90 | 100 | 71 | 29 | 100 | 11 | 14 | 0 | 0 |
| Pakistan | 81 | 95 | 39 | 14 | 86 | 65 | 13 | 9 | 0 | 3 |
| Panama | 38 | 100 | 23 | 62 | 38 | 0 | 14 | 40 | 1 | 0 |
| Papua new guinea | 14 | 15 | 0 | 8 | 92 | 0 | 31 | 9 | 0 | 0 |
| Paraguay | 12 | 74 | 49 | 84 | 16 | 0 | 0 | 6 | 0 | 0 |
| Peru | 11 | 34 | 26 | 66 | 34 | 15 | 27 | 14 | 0 | 0 |
| Philippines | 90 | 91 | 0 | 1 | 99 | 0 | 17 | 16 | 9 | 0 |
| Poland | 123 | 100 | 71 | 0 | 100 | 0 | 1 | 28 | 4 | 0 |
| Portugal | 62 | 91 | 7 | 32 | 68 | 0 | 20 | 8 | 3 | 0 |
| Qatar | 0 | 65 | 100 | 100 | 0 | 100 | 10 | 1 | 0 | 0 |
| Romania | 68 | 98 | 12 | 30 | 70 | 0 | 10 | 5 | 1 | 2 |
| Russian federation | 56 | 82 | 2 | 31 | 69 | 0 | 10 | 8 | 0 | 0 |
| Rwanda | 142 | 100 | 87 | 0 | 100 | 0 | 29 | 8 | 10 | 0 |
| Saudi arabia | 40 | 60 | 100 | 33 | 67 | 100 | 6 | 38 | 0 | 0 |
| Senegal | 36 | 82 | 31 | 57 | 43 | 0 | 3 | 11 | 0 | 1 |
| Sierra leone | 21 | 27 | 1 | 24 | 76 | 0 | 10 | 5 | 2 | 0 |
| Singapore | 0 | 100 | 100 | 0 | 100 | 0 | 0 | 0 | 0 | 0 |
| Slovakia | 0 | 100 | 100 | 0 | 100 | 0 | 0 | 0 | 0 | 0 |
| Slovenia | 25 | 56 | 9 | 56 | 44 | 0 | 26 | 7 | 3 | 0 |
| Somalia | 35 | 100 | 100 | 65 | 35 | 66 | 5 | 1 | 0 | 0 |
| South africa | 42 | 100 | 100 | 58 | 42 | 41 | 12 | 6 | 1 | 1 |
| Spain | 72 | 96 | 9 | 25 | 75 | 0 | 20 | 10 | 3 | 0 |
| Sri lanka | 59 | 71 | 4 | 17 | 83 | 0 | 9 | 23 | 8 | 0 |
| Sudan | 22 | 88 | 90 | 75 | 25 | 39 | 5 | 5 | 0 | 0 |
| Suriname | 1 | 2 | 0 | 27 | 73 | 0 | 0 | 12 | 0 | 0 |
| Swaziland | 26 | 100 | 100 | 74 | 26 | 6 | 22 | 3 | 2 | 1 |

|  | Land utilisation rates |  |  | Share of pasture |  | Adjustments (percent of total land area) |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
| Crountry | Crops on cult. land | Crops and pasture on cult. land | Pasture on grazable land | on cultivable land | on grazable land | Desert | Steepness | Protected | Settlement on cultiv. land | Settlement on graz. land |
| Sweden | 77 | 84 | 1 | 7 | 93 | 0 | 2 | 10 | 1 | 0 |
| Switzerland | 73 | 100 | 68 | 27 | 73 | 0 | 31 | 29 | 6 | 0 |
| Syrian arab republic | 71 | 100 | 91 | 29 | 71 | 25 | 10 | 2 | 1 | 2 |
| Tajikistan | 36 | 100 | 35 | 64 | 36 | 8 | 26 | 18 | 0 | 1 |
| Tanzania | 18 | 100 | 100 | 82 | 18 | 0 | 14 | 40 | 1 | 0 |
| Thailand | 125 | 100 | 21 | 0 | 100 | 0 | 26 | 21 | 4 | 0 |
| Togo | 90 | 100 | 31 | 10 | 90 | 0 | 7 | 11 | 2 | 0 |
| Trinidad and tobago | 100 | 100 | 4 |  |  | 0 | 22 | 6 | 7 | 0 |
| Tunisia | 64 | 100 | 100 |  |  | 69 | 14 | 2 | 1 | 1 |
| Turkey | 51 | 81 | 26 | 37 | 63 | 0 | 27 | 4 | 1 | 2 |
| Turkmenistan | 39 | 100 | 57 | 61 | 39 | 3 | 1 | 4 | 0 | 0 |
| Uganda | 115 | 100 | 87 | 0 | 100 | 0 | 10 | 26 | 4 | 0 |
| Ukraine | 76 | 89 | 23 | 15 | 85 | 0 | 1 | 4 | 1 | 1 |
| United arab emirates | 44 | 81 | 100 | 45 | 55 | 100 | 4 | 5 | 0 | 0 |
| United kingdom | 122 | 100 | 100 | 0 | 100 | 0 | 5 | 31 | 7 | 0 |
| United states of america | 69 | 100 | 62 | 31 | 69 | 12 | 14 | 28 | 1 | 0 |
| Uruguay | 9 | 94 | 22 | 90 | 10 | 0 | 4 | 0 | 1 | 0 |
| Uzbekistan | 40 | 100 | 69 | 60 | 40 | 7 | 3 | 5 | 0 | 2 |
| Venezuela | 36 | 100 | 100 | 64 | 36 | 1 | 16 | 72 | 1 | 0 |
| Viet nam | 97 | 100 | 4 | 3 | 97 | 0 | 33 | 5 | 8 | 0 |
| Western sahara | 0 | 100 | 100 |  |  | 0 | 0 | 0 | 0 | 0 |
| Yemen | 65 | 100 | 100 | 35 | 65 | 93 | 7 | 1 | 0 | 0 |
| Yugoslavia | 71 | 100 | 14 | 29 | 71 | 0 | 21 | 0 | 3 | 1 |
| Zambia | 24 | 100 | 68 | 76 | 24 | 0 | 4 | 41 | 0 | 0 |
| Zimbabwe | 25 | 98 | 50 | 74 | 26 | 8 | 6 | 15 | 0 | 1 |