Modeling land physically in CGE models: new insights on intensive and extensive margins

Xin Zhao [a, *], Dominique Y van der Mensbrugghe [a], Wallace E. Tyner [a]

[a] Department of Agricultural Economics, Purdue University, 403 West State Street, West Lafayette, IN 47907;

* Corresponding Author. Email: zhao269@purdue.edu, Telephone: 7654763288

Abstract

The constant elasticity of transformation (CET) function has been widely used in handling land heterogeneity in computable general equilibrium models. One drawback of the standard CET approach is that physical land cannot be directly traced and preserved during transformation. Although it is claimed that CET effectively adjust land productivity change based on assumptions in line with Ricardo's law of rent, studies focus on land use have to translate effective hectares to physical hectares based on additional assumptions. The present study provides an alternative approach to the CET land transformation in which we take advantage of the additive form of CET (ACET) which permits physical land transformation while adjusting for land productivity during transformation using land-biased technical shifters from the land demand in production. We demonstrated that the new approach can reach identical equilibrium in non-land markets with those from the standard CET approach while, from the new approach, physical land use change results are provided and the land productivity change during the transformation can be adjusted in a more flexible manner. Furthermore, modeling land physically provides many advantages. It allows incorporating responses from cropping intensity by introducing crop harvest frequency (CHF) as a variable in the model. It also permits disaggregating the yield responses due to land productivity heterogeneity. In this study, we focus on providing modeling implications for the new approach and testing the sensitivity of several key intensive and extensive margin responses using a simple CGE model developed for the purpose of this study, despite that more careful future efforts are necessary for calibrating some important parameters.

Keywords: CET, additive CET, Land heterogeneity, Crop intensity, CGE

1. Introduction and motivation

1.1. Physical land or "effective land" in CGE framework

In a computable general equilibrium (CGE) framework, constant elasticity of substitution (CES) and constant elasticity of transformation (CET) functional forms are widely used in modeling input demand in production and sluggish endowment supply, respectively. The two functional forms are identical except the sign determining their concavity (Arrow et al., 1961; Powell and Gruen, 1968). Land is classified as a sluggish endowment commodity because it is imperfectly mobile and heterogeneous in quality, which may lead to different prices across sectors (Hertel and Tsigas, 1996). Fig 1 presents an example of the CES-CET nesting framework for land demand in crop production (top panel) and land supply (bottom panel). The red arrow indicates the land market clearing condition for a cropland. Crop yield is the ratio of crop production over crop harvested area. Due to the heterogeneity in land quality, when a crop is expended on either new cropland (from forest or pasture) or existing cropland (originally used for the production of other crops), the crop yield in production is likely to be different from the yield of the existing crops (Tyner et al., 2010). The standard CES land demand is not capturing land heterogeneity so that newly converted land is deemed the same with the existing land in crop production. Yet, the productivity of new land is "effectively" accounted for during the CET land transformation (Golub et al., 2009).

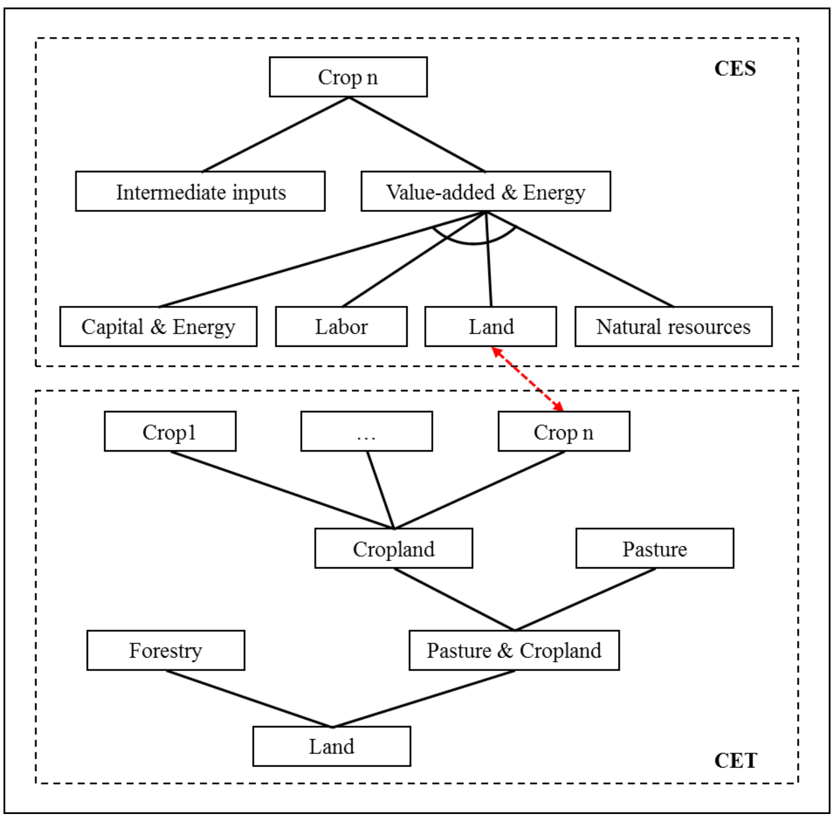
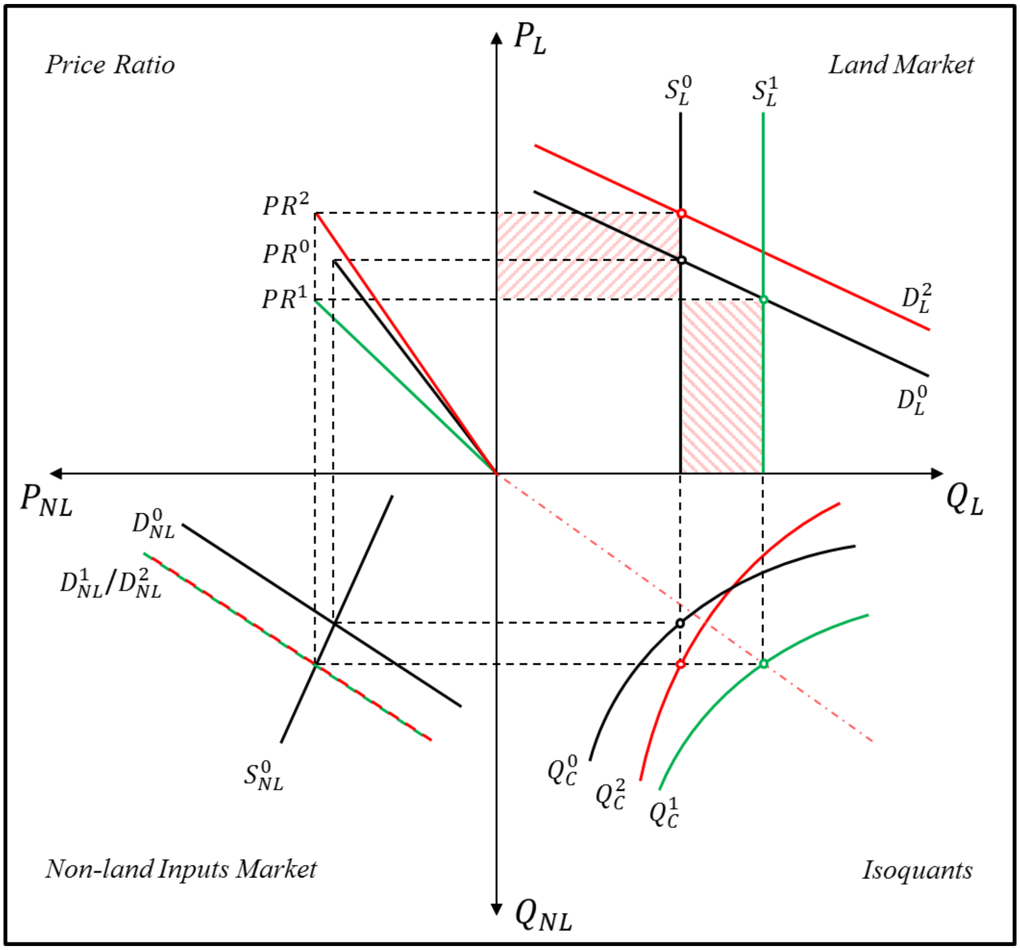


Fig. 1 Nesting framework for land demand in crop production (top panel) and land supply (bottom panel)

In CGE models, a factor productivity change is usually imposed from shifting a "effective factor" supply, in which "effective factor" endowments can take into account both the quantity and the efficiency of a factor (Burfisher, 2011). Although a factor productivity change may be more practical in implementation from the factor supply side than from the demand side, it is important to note that in doing so, the factor market equilibrium would represent "effective factor" rather than physical factor. Fig. 2 presents a partial equilibrium example of producing an aggregated crop (the only land-use sector) using land and non-land inputs, assuming a perfectly elastic crop demand. The aggregate land supply is inelastic because the total endowment is fixed which represents a standard CGE assumption. The notations are presented in the figure note. Equilibrium 0 ($b = 0$, black lines) represents the initial equilibrium. In the traditional approach, when land productivity increases, the initial land supply (S_L^0) is shifted to the "effective land" supply (S_L^1), and the new equilibrium is represented by equilibrium 1 ($b = 1$, green lines). It encourages a lower "effective land" price and increases in crop production and non-land inputs demand. As a result, the price ratio between "effective land" and non-land inputs becomes smaller (PR^0 to PR^1) so that the "effective yield" decreases due to factor substitutions. An alternative approach to striking a land productivity change is to adjust land demand in crop production with a land biased technical shifter in crop production (equilibrium 2 in Fig. 2, $b = 2$, red lines). The isoquant of crop production becomes steeper, implying that less land is needed in producing the same amount of crop. In this case, land demand in per unit production decreases while land demand curve may shift up or down depending on non-land input supply elasticity and crop production technology (Fig. 2 demonstrates a case of shifting up D_L^2 and the case of shifting down D_L^2 is presented in Fig. A1). If the shifter on "effective land" supply in the first approach and the land biased technical shifter in the second approach are commensurate, the two approaches of implementing a land productivity change would result in identical equilibria in the non-land inputs market (D_{NL}^1 and D_{NL}^2 overlaps) and the crop market ($Q_C^1 = Q_C^2$). The difference is that the first approach provides the "effective land" market equilibrium while the second approach provides the physical land market equilibrium. The two shaded areas in Fig. 2 are the same in size since the total land rental revenue should be the same between the two approaches.



Note: the notations in the figure can be represented by X_a^b, whereas

$$X = \begin{cases} D: demand \\ S: supply \\ Q: quantity \\ P: price \\ PR: price\ ratio\ between\ land\ and\ nonland\ inputs \end{cases}$$

$$a = \begin{cases} L: land \\ NL: nonland \\ C: crop \end{cases} \qquad b = \begin{cases} 0: initial\ equilibrium \\ 1: equilibrium\ with\ effective\ land\ supply\ shifter \\ 2: equilibrium\ with\ land\ biased\ technical\ shifter \end{cases}$$

Fig. 2 Two approaches of implementing a land productivity change in CGE models.

When it comes land transformation, it is claimed that CET is "effectively" addressing the productivity heterogeneity besides physically transforming land across sectors (Golub et al., 2009). It was because the CET transformed lands are land rental share-weighted as a result of maximizing land owner's rental revenue. Based on the assumption that land rents would reflect land quality or productivity (Ricardian rent), the transformed lands on the CET frontier can be explained as productivity-weighted land or "effective land" (Golub et al., 2009). For example, when a relatively low rental/productivity land (e.g., forest or pasture) is converted to a relatively high rental/productivity land (e.g., cropland), the increase in the higher-productivity land will be smaller than the decrease in the lower-productivity land due to the disparity in land rental/productivity. The difference in the productivity of new land is effectively accounted for in a way that sacrifices physical land market equilibrium while maintaining the general equilibrium in non-land markets. In other words, during the CET land transformation among land-use sectors, there is an implicit "effective land" supply shifter promoting an equilibrium of "effective land". Nevertheless, two important issues may arise, (1) the physical land cannot be traced since there is no inherent mapping between "effective land" and physical land during the CET transformation; and (2) the assumption that land rents imply land productivity may not necessarily hold in reality[1], given that land productivity differences may be not the only reason land rentals are different. In a study focuses on land use change related issues, a model can directly produce physical land use results and can be flexible on governing the extent of land productivity adjustment during transformation should be strictly preferred. Thus, one of the motivations of this study is to seek an appropriate alternative approach that permits modeling land transformation physically and accounting for land productivity heterogeneity in a more flexible manner.

1.2. Intensive and extensive yield margins

Equations (1-3) depict factor markets equilibria in agricultural production in a model in which producers minimize cost and the production is assumed to be locally constant returns to scale thus generating zero economic profits (Keeney and Hertel, 2009). Demand of the output is assumed to be perfectly elastic to make commodity output price exogenous (consistent with Fig. 2). c denotes input cost shares in production so that equation (3) represents the zero-profit condition for the cost minimizing producer. With a shock in the output price, percentage changes in factor supplies and demands (x^s, x^d), input and output prices (r, p), and the output (q) can be resolved. Factor mobility of input i is governed by the factor supply elasticity, η_i. $\varepsilon_{i,j}$, the output constant elasticity of demand for input i to the price of j, is equal to the product of the Allen-Uzawa elasticity of substitution (AUES or $\sigma_{i,j}$) and c_j. $\sigma_{i,j}$ captures the factor substitution in production. Both η_i and $\sigma_{i,j}$ are critical in determining commodity output supply elasticity and the economic equilibrium (Keeney and Hertel, 2009).

$$x_i^s = \eta_i r_i \qquad (1)$$

$$x_i^d = \sum_j \varepsilon_{i,j} r_j + q \qquad (2)$$

$$p = \sum_i c_i r_i \qquad (3)$$

To avoid ambiguity, we define intensive yield margin as responses affecting land demand in production and extensive yield margin as responses affecting land supply. Apparently, land mobility, governed by η_{land}, is a supply margin response and the substitution between land and other factor inputs, captured by $\sigma_{land,j}$ is a demand margin response. However, another important response representing the land productivity change was not modeled in the above framework. As demonstrated by Fig. 2, the land productivity change can be implemented either from the land supply side with the shifting effective land approach or from the land demand side

[1] David Ricardo's law of rent may work better within a single use of land, but may not work well across different use of land.

with the land biased technical shifter approach. Thus, it can be counted as either intensive or extensive margin. Also, the land productivity change can be categorized in to two types, (1) exogenous land productivity changes due to the improvement of land use technologies (e.g., soil conservation technologies) and (2) endogenous land productivity adjustments due to land transformation. The present study focuses on investigating the second type of the land productivity change.

When modeling land supply using the standard CET approach, the land supply (x_m^s, for land type m) in equation (1) becomes the CET land supply described in equation (4).

$$x_m^s = \sum_n \delta_{m,n} r_n + y \qquad (4)$$

$\delta_{m,n}$ are the output constant elasticity of supply for land m to the price of land n. y is the percentage change in the total land supply which is usually zero. $\delta_{m,n}$ are determined by the nesting structure, elasticities of substitution, and rental shares of land n. As discussed earlier, CET implicitly accounts for land productivity heterogeneity during transformation using the approach of shifting effective land. Thus, $\delta_{m,n}$ in equation (4) are capturing both land mobility and land productivity changes during transformations. Because of this, results from CET land transformation are in degenerate forms that the two extensive margin responses cannot be distinguished. Based on the intuition implied by Fig. 2, one promising solution is to, instead of capturing the productivity changes due to transformation from supply side, implement the productivity changes from land demand side by adjusting production while also applying a physical land transformation approach for modeling land supply. Another motivation of this study is to explore the sensitivity of key intensive and extensive margin responses within the new framework proposed in this study.

A recent study from van der Mensbrugghe and Peters (2016) developed an additive form of CET function (ACET) for land transformation. ACET permits physical land transformation across sectors while it does not adjust land productivity during the transformation. In the present study, we take advantage of the ACET land transformation approach to disaggregate the endogenous land productivity adjustment factor embedded in the standard CET approach. We demonstrate that implementing the land productivity change using the intensive margin approach can reach equivalent results for non-land markets. In this sense, land can be physically traced via ACET and land productivity can be adjusted more flexibly by either following the “effect land” adjustment implied by standard CET or possibly incorporating new information.

Several valuable benefits from modeling land physically in CGE models includes:

1) The physical land use change results are directly provided by the model. This permits shocking land use directly in a simulation for land-related policy analysis.

2) The original elasticity of land transformation can be disaggregated into pure acreage responses (land mobility) and yield responses due to land productivity heterogeneity in transformation. It permits understanding and tracking land supply/mobility responses and different types of yield responses so that land supply elasticities and yield elasticities from literature can be better applied and reflected in a model.

3) It permits incorporating extensification responses from multiple cropping practices or unused existing cropland (MC/UL) by introducing new variables such as crop harvest frequency (CHF) or specific crop intensity index (SCII) and associating the variables with economic variables such land prices within the model framework. MC/UL responses

are rarely modeled explicitly due to the challenges from non-traceable land supply, data availability, and theoretical linkage in the model. MC/UL responses can be critical in land use modeling (Taheripour et al., 2016).

4) Upon disaggregating the yield responses due to land productivity heterogeneity, it provides a possibility of introducing biophysical information to determining land productivity.

A thorough study of all these may entail efforts of a stream of studies, given the broad scope of these benefits. In the present study, we provide modeling implications for all these aspects, and focus on testing the sensitivity of several key intensive and extensive margin responses using a simple CGE model developed for the purpose of this study. The rest of this paper is organized as follows. Section 2 reviews land modeling approaches in CGE literature. The derivation of ACET and the decomposition are presented in section 3. In section 4, we build a small-scale CGE model with 3 regions and 7 industries. Experiments are designed based on the model to compare the standard CET approach with the ACET approach. Results are explained and discussed in section 5 and section 6 concludes the study.

2. Literature review

Since being introduced by Hertel and Tsigas (1996) for handling land heterogeneity into the standard Global Trade Analysis Project (GTAP) model, the CET functional form has become prevalent in modeling land supply in well-known global economic equilibrium models, such as GTEM (Ahammad and Mi, 2005), GTAP-AEZ (Hertel et al., 2009a), GTAP-BIO (Hertel et al., 2010; Tyner et al., 2010), ENVISAGE (van der Mensbrugghe, 2010), MIRAGE (Al-Riffai et al., 2010), and MAGNET (van Meijl et al., 2006; Verburg et al., 2009). These models have been heavily employed for examining impacts such as climate change, trade liberalization, or biofuels policies have on global land use change and the associated greenhouse gas emissions. In GTAP models, to trace land transformation with the CET approach, the “ad hoc” adjustments were developed to translate the “effective land” to physical land. An elasticity of effective cropland with respect to cropland expansion (ETA) parameter was introduced to govern the productivity of new cropland relative to the existing cropland. The parameter was derived mainly using the net primary production (NPP) data from the Terrestrial Ecosystem Model (TEM) for each agro-ecological zone (AEZ) in a region (Taheripour et al., 2012; Tyner et al., 2010). The ETA parameter was first employed to adjust the cropland area. Two endogenous slack variables were then applied to, respectively, (1) adjust the volume of CET-transformed forest and pasture to preserve the physical land area, and (2) adjust the volume of CET-transformed crop harvested areas based on an assumption that the change in total harvested area equals the change in cropland cover[2] (Hertel et al., 2010). These adjustments were made based on ex post equilibrium values so that they did not affect the market clearing condition. However, as Valin et al. (2013) and Fujimori et al. (2014) indicated, the “ad hoc” treatment for preserving area additivity is a compromise solution. Hertel et al. (2009b) implied the CET function “covers a multitude of sins” and called for a more explicit approach to handle land heterogeneity.

Several studies have tested alternative function forms to the standard CET to preserve volume in land transformation. In the Agriculture and Land Use (AgLU) model, Sands and

[2] Taheripour et al. (2016) relaxed this assumption in studying intensifications in crop production through multiple cropping practice or use of existing unused cropland.

Leimbach (2003) developed a logit approach for land transformation, which was derived from the maximization of the economic return of land subject to the area-preserving constraint and an explicitly defined joint probability distribution of yield in each region. Wise et al. (2014) introduced the logit approach to the Global Change Assessment Model (GCAM) for studying agricultural production, land, and terrestrial carbon. Fujimori et al. (2014) compared the logit approach with the CET approach on modeling land supply in the Asia-Pacific Integrated Model (AIM) and concluded that the area balance violation for CET was small for the aggregated world total, but relatively large and heterogeneous across regions. In empirical studies, it is difficult to match logit-sharing parameters with yield distributions that imply land quality. Thus, the idea of distribution of yield or land profitability serves more as an interpretation of the model specification than as an instrument for parameter calibration. In another stream of studies, Dixon and Rimmer (2003) initially developed an additive form of CES for allocating labor across sectors and unemployment categories. The additive form of CES was derived by solving a utility maximizing problem subject to a labor volume-preserving condition whereas the utility function was defined as the CES aggregation of incomes. Following the intuition, the additive form of constant ratio of elasticity of transformation, homothetic (CRETH) function[3] and the additive form of CET function (ACET) were developed and applied to allocating land to different sectors physically (Giesecke et al., 2013; Mariano and Giesecke, 2014; van der Mensbrugghe and Peters, 2016). They were derived from maximizing a CRETH or CET aggregation of the land revenues which was defined as the utility of land owners, subject to the area-preserving constraint. van der Mensbrugghe and Peters (2016) also demonstrated that the initial prices do not affect the percentage results from a model when using the standard CET formulation, while they do matter in the ACET formulation since the initial volume information is needed when using the ACET formulation. Besides new functional forms, an alternative approach is to incorporate land conversion costs by depicting a complete transformation process so that the area discrepancy can be attributed to the costs of conversion. This approach was introduced by Gurgel et al. (2007) to the MIT Emissions Prediction and Policy Analysis (EPPA) model. Nevertheless, this method requires additional data on land conversion costs and timber harvesting. The costs of land conversion cannot fully interpret landowners' behavior given that there are other non-market costs. Also, the calibrated elasticity of transformation, which governs the ease of land mobility, may have partially considered land conversion costs since the elasticity may be viewed as mirroring the factors that reach beyond agronomic consideration but impede land mobility, such as costs of conversion, management practices, technology accessibility, unmeasured benefits from crop rotation, etc. (Giesecke et al., 2013; Golub et al., 2010).

To our knowledge, there is a direct mapping between ACET and the logit approach based on the logit sharing functional form presented in Fujimori et al. (2014) and Wise et al. (2014). Also, given that the CES-CET land modeling approach is the most commonly seen in the literature and ACET is directly comparable with CET, we concentrate on investigating the ACET approach and comparing it with the standard CET approach. The objective of this study is to develop a consistent and communicable approach to modeling land physically in CGE models. The approach development aims to provide a promising alternative to the standard CET plus the "ad hoc" adjustment approach.

[3] Constant ratio of elasticity of substitution, homothetic (CRESH) and constant ratio of elasticity of transformation, homothetic (CRETH) are more generalized functional form of CES and CET, respectively. See Vincent et al. (1980) for detail.

3. Methodology

The standard CET land transformation approach is performing two tasks including (1) transforming land on a physical basis and (2) adjusting transformed land productivity. In this study, we will separate the two tasks by (1) using the ACET approach developed by van der Mensbrugghe and Peters (2016) to model land supply physically and (2) adjusting land productivity from land demand in production. The ACET approach is modified to incorporate crop harvest frequency (CHF) as a variable. It permits modeling the multiple cropping and the use of unused cropland (MC/UL) as an extensive margin response. CHF, also known as cropping intensity is defined as a ratio between the total harvested area and cropland cover so that responses from multiple cropping and unused cropland cannot be distinguished without additional data. Also, we decompose ACET from the perspective of the standard CET, for comparison purpose between CET and ACET.

3.1. Additive CET

According to van der Mensbrugghe and Peters (2016), the additive form of CET function is derived from maximizing the utility which is a CET aggregation of land rental revenues (equation 5), subject to the area-preserving condition (equation 6). The area-preserving condition is modified to incorporate CHF, φ. P_i are land rents and X_i are land areas. Y is the total land area. g_i are CET parameters. u is the CET exponent. $u = \omega/\omega + 1$ whereas ω is the absolute value of the elasticity of transformation.

$$\max_{X_i} \; Utility = \left[\sum_i g_i (P_i X_i)^u\right]^{\frac{1}{u}} \tag{5}$$

$$s.t. \qquad Y = \frac{1}{\varphi} \cdot \sum_i X_i \tag{6}$$

In equation (6), φ will be set to 1 if the land transformation is among land covers or among harvested areas. Only in the case of transforming from cropland cover to harvested area, φ comes into play. The solution as the supply of X_i can be derived through first order conditions,

$$X_i = \frac{g_i^{1+\omega} \cdot P_i^{\omega}}{\sum_j g_j^{1+\omega} \cdot P_j^{\omega}} \cdot \varphi \cdot Y \tag{7}$$

The aggregated land price, P, can be derived using the zero-profit condition,

$$P = \frac{\sum_j g_j^{1+\omega} \cdot P_j^{1+\omega}}{\sum_j g_j^{1+\omega} \cdot P_j^{\omega}} \cdot \varphi \tag{8}$$

The log-differentiation form of equation (7) can be derived as

$$\hat{X}_i = \hat{Y} + \omega \hat{P}_i - \omega \sum_j \left(s_j \hat{P}_j\right) + \hat{\varphi} \tag{9}$$

Hat (^) denotes proportional change throughout this study ($\hat{X} = \Delta X/X$), and s_i denotes volume shares, $s_i = X_i / \sum_j X_j$.

3.2. Additive CET decomposition

To compare ACET with CET, we decompose ACET and technical shifters from CET and explain the shifters as the implicit land productivity adjustments imbedded in CET. Denote θ_i as land rental shares, $\theta_i = P_i X_i / \sum_j P_j X_j$. Manipulating equation (9) to derive equation (10),

$$\hat{X}_i = \hat{Y} + \omega \hat{P}_i - \omega \sum_j \theta_j \hat{P}_j - \omega \sum_j \left[\left(s_j - \theta_j \right) \hat{P}_j \right] + \hat{\varphi} \tag{10}$$

Decomposing equation (9) with equations (11) and (12), and introducing a scale factor μ (μ =1) into $\hat{\alpha}$,

$$\hat{X}_i = \hat{Y} + \omega \hat{P}_i - \omega \sum_j \theta_j \left(\hat{P}_j \right) - \hat{\alpha} + \hat{\varphi} \tag{11}$$

$$\hat{\alpha} = \mu \cdot \omega \sum_i \left[(s_i - \theta_i) \hat{P}_i \right] \tag{12}$$

Equation (11) is identical to the supply function derived from the standard CET approach with $\hat{\alpha}$ being a neutral technical shifter. It indicates that ACET plus $\hat{\alpha}$ is equivalent to standard CET. The decomposition demonstrates that a technical shifter capturing land productivity change can explain the difference between CET and ACET. The CHF (φ) variable was introduced as a neutral technical shifter in land supply, which implies that the application of multiple cropping practice or the use of unused land (MC/UL) can be another source ($\hat{\varphi} > 0$) or sink ($\hat{\varphi} < 0$) of crop harvested area. $\hat{\varphi}$ can be further endogenized by constructing a link with economic variables such as land prices. Similar to CHF, the specific crop intensity index (SCII) can be introduced in the area preserving condition to distinguish crops by their abilities of multiple cropping or use of unused cropland. SCII is not modeled here since it is not the focus of this study. Appendix B provides an alternative approach for deriving ACET and decomposition, reaching the same results (SCII was included in the derivation).

With the technical neutral shifter, the derivations in equation (11) and (12) attribute the productivity change to all lands associated with the transformation. An explanation can be that within each type of land, there is a distribution with respect to the land productivity. That is, there is also heterogeneity within a same type of land. During the land transformation from low productivity/price land to a high productivity/price, the best land in the low productivity/price land is converted first. As a result, in addition to adjusting the productivity of new land to represent its lower productivity, the land productivity of the existing low productivity/price land also need to be adjusted down to reflect lower average value. The technical neutral shifter assumes the two adjustments in the example are equal in scale.

In a broader perspective, the decomposition can be also conducted using biased technical shifters, λ_i. Equation (13) is the standard CET land supply with λ_i but no α. The decomposition condition becomes equation (14).

$$\hat{X}_i = \hat{Y} + \omega \left[\hat{P}_i - \sum_j \theta_j \left(\hat{P}_j - \hat{\lambda}_j \right) \right] - (1 + \omega) \hat{\lambda}_i + \hat{\varphi} \tag{13}$$

$$\sum_j \left[\omega \left(s_j - \theta_j \right) \hat{P}_j \right] - \sum_i \hat{\lambda}_i \left[s_i + \omega (s_i - \theta_i) \right] = 0 \tag{14}$$

Note that the solution of λ_i is not unique. when λ_i are all equal, they collapse into the technical neutral shifter α. If attributing productivity change solely to the newly converted land m, then

$\hat{\lambda}_{-m}$ should be zero and $\hat{\lambda}_m$ becomes $\sum_j \left[\omega\left(s_j - \theta_j\right)\hat{P}_j\right] / [s_m + \omega(s_m - \theta_m)]$. However, in practice, the biased technical shifters are difficult to implement since it requires the information of land transformation direction to know land m.

Using either technical neutral or biased shifter, land productivity adjusted based on land rent, with different explanations though. The technical shifter implementation in CET can be explained the case illustrated by equilibrium 1 in Fig. 2. Following the intuition from the equilibrium 2 in Fig. 2, one hypothesis is that if implementing $\hat{\alpha}$ or $\hat{\lambda}_i$ as land biased technical shifter from land demand side in production, the non-land market equilibria should remain unchanged. It is important to note that by nesting ACET land supply, the land productivity adjustment from the neutral technical shifter approach are differentiated across sectors. In this study, we focus on testing the hypothesis for the technical neutral shifter $\hat{\alpha}$. This is tested by comparing experiment 1 and experiment 3 in section 4. Furthermore, μ is introduced as a scale factor parameter in $\hat{\alpha}$. When implementing $\hat{\alpha}$ in an ACET frame work to mirror a CET-like land productivity adjustment, varying μ provide flexibility in controlling the extent of land productivity adjustment. In this sense, μ is a parameter governing extensive margin response of land productivity adjustments due to land transformation. Alternatively, the technical shifters can be introduced hinging on exogenous biophysical information such as net primary production. This requires further study with a model in finer resolution.

3.3. Welfare decomposition

With the application of ACET, equations for welfare decomposition may be different with conventional ones due to the disparities between ACET ("effective land") and CET (physical land). We derive the welfare decomposition equations following the equivalent variation (EV) decomposition developed by (Huff and Hertel, 2000) for GTAP models. One condition used in the original derivation implied by the standard CET approach which was the market land price index equals to land rental weighted land prices.

$$\hat{P} = \sum_i \hat{P}_i \theta_i \tag{15}$$

This equation is the zero-profit condition under the standard CET approach in which land owners were modeled as revenue maximizer. However, it is not hold with ACET in which land-owners are utility maximizer and the complete zero-profit condition has to be applied. Thus, terms canceled based on the relationship should be brought back. The revised EV decomposition equations in GEMPACK code are shown in Appendix C (see Huff and Hertel (2000) for more details). The contribution of EV changes from endowment change was modified accordingly. Welfare decomposition results are discussed based on designed experiments.

4. Modeling framework and experimental design

4.1. Modeling framework

For the purpose of comparing CET and ACET in land transformation and investigating the sensitivity of intensive and extensive margin responses, we develop a small-scale CGE model based on the standard GTAP framework and assumptions (Hertel and Tsigas, 1996). Private households maximize a constant difference of elasticity (CDE) utility function subject to a budget constraint. Producers minimize cost with nested CES production function earning zero pure profit. The Armington structure is used for international trade. We employ GTAP 9 data base (Aguiar et al., 2016) while the data base is aggregated to three regions including the USA, EU, and rest of the world (ROW), and seven sectors including grain, other crops, livestock, food, manufacture, forestry, and service. The sector mapping from GTAP data base to the data base used in this study is shown in Table A1. Endowment commodities include capital, labor, land, and natural resources. Capital and labor are mobile goods that can freely move across sectors. A general production nesting structure is presented in Fig. 3. The land supply nesting structure remains the same with the bottom panel in Fig. 1 except that there are only crop harvested areas for grain and other crops. We use GTAP land data base developed by Peña-Lévano et al. (2015). The data base represents an economic equilibrium in 2011. For the purpose of this study, we test how mandating a 10% increase in domestic grain consumption in food sector in the USA affect land use change. The same simulation test is used to compare different land modeling approaches. Table 1 presents production cost shares at agents' price in the USA in the initial data base. There are four land-use sectors. Grain cost accounts for 2% in producing food sector commodities. A subsidy on grain consumption in food sector may encourage the total grain production and thus grain land demand. The new grain land can only come from land being used by other crops, livestock (pasture), and forestry (accessible forest). The mandate may also influence productions in other sectors, household consumptions, and international trade.

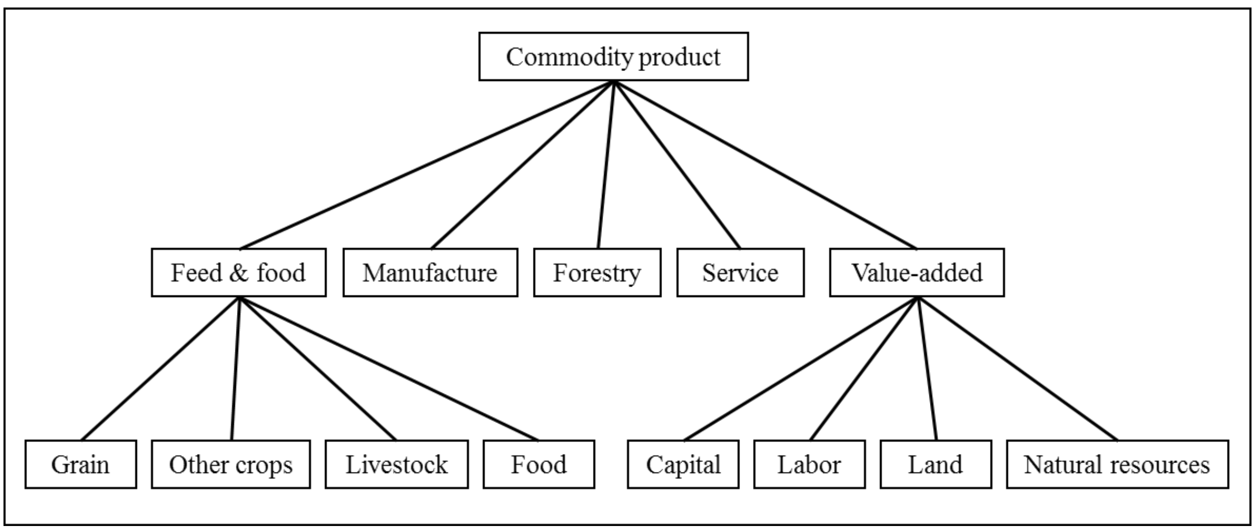


Fig. 3 CES nesting structure in production

Table 1 Production cost shares at agents' price in the USA

	Grain	Other crops	Livestock	Forestry	Food	Manufacture	Service
Land	14%	17%	7%	30%	0%	0%	0%
labor	17%	20%	8%	8%	18%	23%	45%
Capital	15%	18%	7%	13%	12%	11%	16%
Natural resources	0%	0%	0%	0%	0%	1%	0%
Grain	2%	0%	35%	0%	2%	0%	0%
Other crops	1%	3%	1%	0%	6%	0%	0%
Livestock	0%	0%	4%	0%	8%	0%	0%
Forestry	0%	0%	0%	3%	0%	0%	0%
Food	0%	0%	12%	4%	22%	0%	1%
Manufacture	25%	18%	5%	5%	12%	47%	11%
Service	27%	24%	21%	37%	20%	18%	27%

4.2. Parameterization

Commonly used parameters for CDE derived household demand functions, elasticities for Armington assumptions, and elasticities of factor substitution are provided with the GTAP data base (Aguiar et al., 2016). Table 2 presents several parameters governing intensive and extensive margin responses focused in this study. They are in line with the literature (Keeney and Hertel, 2009; Taheripour and Tyner, 2013).

Table 2 Key parameters

Parameter/variable description	Name	Value	Source
Elasticity of land transformation across forestry and pasture & cropland	ETL1	-0.0186	Taheripour and Tyner (2013)
Elasticity of land transformation across cropland and pasture	ETL2	-0.0218	
Elasticity of land transformation across crop harvested areas within cropland	ETL3	-0.75	
Elasticity of crop yield w.r.t. to crop price	YDEL	0.25	Keeney and Hertel (2009)
Elasticity of substitution among imports from different sources for grain	ESUBM	2.6	Aguiar et al. (2016)
Scale factor governing endogenous land productivity adjustments due to land transformation	μ	1	Author assumption
Exogenous extensive responses from multiple cropping and the use of unused cropland (percentage change in CHF)	$\hat{\varphi}$	0	Author assumption

Note: Given the scope of this study, these parameters are used uniformly across region in this study.

Based on the elasticities of land transformation and land rental shares, the initial cross-price elasticities of land cover supply are derived via AUES for the CET approach (Table 3). The derivation of the land supply matrix for the nested ACET approach is more complicated (Table

4). Both land rental shares and land area shares are required and chain rule is used based on the totally differentiated supply functions. It is important to note that the extensive responses implied by the two approaches may be different since the land supply elasticities implied by CET are in "effective land" while the elasticities in ACET reflect solely physical land mobility. Based on the initial data, these elasticities show that compared with CET, ACET has higher cropland responses ($\delta_{cropland,n}$) but lower pasture responses ($\delta_{pasture,n}$). These differences are mirrored in results when comparing experiment 1 and experiment 2. The calibration of the parameters is not the focal point of this study, despite that more efforts are necessary for ACET parameters calibration in a more advanced model.

Table 3 Cross-price elasticity of land supply for land m (column) to the price of land n (row) using standard CET

$\delta_{m,n}$	Cropland	Pasture	Forest
Cropland	0.004	-0.002	-0.002
Pasture	-0.018	0.020	-0.002
Forest	-0.015	-0.002	0.017

Table 4 Cross-price elasticity of land supply for land m (column) to the price of land n (row) using ACET

$\delta_{m,n}$	Cropland	Pasture	Forest
Cropland	0.019	-0.008	-0.006
Pasture	-0.002	0.009	-0.006
Forest	-0.011	-0.002	0.012

4.3. Experimental design

We use a simulation of shocking a 10% increase in domestic grain consumption in food sector in the USA to study land use change impacts. In particular, five experiments (Table 5) are designed to compare CET with ACET and to test the sensitivity of the key intensive and extensive margin responses. It is worth mentioning that labor and capital mobility, YDEL, and ESUBM are also critical in determining land use change results. However, these responses are rigorously investigated in Keeney and Hertel (2009). Thus, we shed lights on the sensitivity of the intensive margin response of land productivity change during transformation and the extensive margin response of MC/UL in experiment 4 and 5, respectively.

Table 5 Experimental design

Experiment	Description
Experiment 1	Standard CET
Experiment 2	ACET
Experiment 3	ACET, linking technical neutral shifters implied by CET to land demand in production
Experiment 4	Based on experiment 3, testing μ with a range [0, 1]

Experiment 5	Based on experiment 3, testing $\hat{\varphi}$ with a range [0, 1.5%]

5. Results and discussion

5.1. Results from experiments 1-3

Simulation results from experiments 1-3 for the USA are shown in Table 5. A more complete set of results are presented in Table A2. With a 10% mandate increasing grain consumption in food sector in the USA, for all three experiments, the total grain production expanded and other lands were converted to producing grain. This encouraged an increase in crop prices and cropland rents. An interesting result is that pasture rent decreased by over 2% in the USA for all three experiments. The mandate led to a plummet in the grain demand (accounting for 35% of cost share) in livestock production which in turn dampened the livestock sector production. Relative to land, other factors and intermediate inputs are moving to other sectors at a much faster speed so that pasture rent decreased. Similarly, for the other crops sector, production decreased significantly, factors were moving to mainly the grain sector, but land rent of other crops did not decrease because the land mobility from other crops land to grain land was high.

Experiment 1 shows results using CET for land transformation so land sector related results are in "effective land". There is a land cover discrepancy (257 thousand ha land loss) if directly applying "effective land" percentage change to physical land. The change of CHF cannot be conjectured since it is not explicitly modeled. With the shock, the calculated "effective" yield elasticity is 0.24, mirroring the YDEL value. When applying ACET to model land physically (experiment 2), results indicated that the physical land use change results can be very different with the "effective" land use change results (experiment 1). The difference reflects the disparities in elasticities of land supply. The non-land market equilibrium results are identical between experiment 1 and experiment 3. This verified the hypothesis that implementing a same land productivity change shock from either land supply side or land demand side would not affect non-land market equilibrium. However, the demand side implementation approach provided physical land use change results. Note that result differences between experiment 2 and experiment 3 are moderate. This indicated that the effect from the land productivity change during land transformation might be modest for the experiment.

Table 5 Simulation results from experiments 1-3

Simulation results		USA		
Major indicators	Sector	Experiment 1	Experiment 2	Experiment 3
Land use change (%)	Grain	1.625	1.702	1.795
	Other crops	-0.705	-0.514	-0.539
	Livestock	-0.085	-0.026	-0.026
	Forestry	-0.030	-0.018	-0.022
Land rent change (%)	Grain	4.747	4.028	4.572
	Other crops	1.556	1.017	1.387
	Livestock	-2.069	-2.298	-2.127
	Forestry	0.122	0.060	0.113
Harvested area (Thousand ha)	Grain	604	633	667
	Other crops	-736	-536	-563
	Total area	-131	97	105
Land cover (Thousand ha)	Cropland	23	106	114
	Pasture	-214	-66	-66
	Forest	-66	-39	-48
Land cover discrepancy (Thousand ha)		-257	0	0
CHF change		Unknown	0	0
Yield change (%)	Grain	0.162	0.138	-0.008
Yield elasticity	Grain	0.242	0.242	-0.012
Production output change (%)	Grain	1.787	1.840	1.787
	Other crops	-0.642	-0.472	-0.642
	Livestock	-0.377	-0.352	-0.377
	Forestry	-0.021	-0.014	-0.021
Market price change (%)	Grain	0.669	0.570	0.669
	Other crops	0.267	0.177	0.267
	Livestock	0.074	0.021	0.074
	Forestry	0.033	0.015	0.033

Due to the market distortion, the EV welfare increased for the USA but decreased in EU and ROW, and the overall world welfare decreased. EV welfare decomposition results from experiments 1-3 for the USA are presented in Table 6. EV decomposition may be different when modeling land physically since the EV change due to land productivity change can be disaggregated. Compared with experiment 1, experiment 2 had a higher EV since the lower land productivity due to, in this case, transforming low productivity land to higher productivity land had not been considered. Experiment 3 had a same total EV results with experiment 1, but the decomposition provided additional insights. In experiment 3, physical land transformation encouraged $85 MM welfare increase while the change in technology which represented the land productivity changes implemented from land demand offset $67 MM. These two effects were aggregated in to allocative efficiency in experiment 1 so that there was also $18 MM loss in allocative efficiency in experiment 3 compared with experiment 1.

Table 6 EV welfare decomposition in experiments 1-3 for the USA

EV decomposition	USA		
	Experiment 1	Experiment 2	Experiment 3
Endowments	0	80	85
Allocative efficiency	-81	-116	-99
Terms of trade	204	168	204
Capital goods and saving	15	37	15
Technology	0	0	-67
Total EV (2011 MM $)	138	169	138

5.2. Results from experiments 4-5

The land productivity adjustments implemented in experiment 3 was decomposed from CET. In experiment 4, the sensitivity of the land productivity adjustments scale factor (μ) was tested for μ in [0, 1]. When $\mu = 0$, the experiment becomes experiment 2 and when $\mu = 0$, it becomes experiment 3. Table 7 presents land use change results and yield elasticities with different μ. It indicated that land use change results were not sensitive to the land productivity changes due to land transformation in the scale factor range. However, the grain yield elasticity decreased significantly with the increase in μ. It indicated that in calibrating crop yield elasticity, land productivity change during land transformation may play an important role.

Table 7 Experiment 4 results for the USA

USA	Land productivity adjustments scale factor, μ										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Grain area (%)	1.702	1.711	1.720	1.729	1.738	1.747	1.756	1.766	1.776	1.785	1.795
Other crops area (%)	-0.514	-0.516	-0.519	-0.521	-0.524	-0.526	-0.529	-0.531	-0.534	-0.537	-0.539
Cropland (%)	0.068	0.069	0.069	0.070	0.071	0.071	0.072	0.072	0.073	0.073	0.074
Pasture (%)	-0.026	-0.026	-0.026	-0.026	-0.026	-0.026	-0.026	-0.026	-0.026	-0.026	-0.026
Forest (%)	-0.018	-0.018	-0.019	-0.019	-0.020	-0.020	-0.020	-0.021	-0.021	-0.022	-0.022
Grain yield (%)	0.138	0.124	0.110	0.096	0.081	0.067	0.053	0.038	0.022	0.008	-0.008
Grain yield elasticity	0.242	0.214	0.187	0.161	0.133	0.109	0.085	0.060	0.034	0.012	-0.012

In experiment 5, we test how a change in $\hat{\varphi}$ affect results in experiment 3. Some key results are presented in Table A3. With an increase in CHF, the supply of harvested area increased relative to cropland cover. Thus, the total harvested area increased while cropland cover followed a decreasing trend as CHF increased (Fig. 4). Land prices and crop prices decreased with the increase in CHF. Aiming to provide implications for making CHF endogenous in the model, CHF elasticity with respect to cropland price was calculated (Fig. 5). It indicated that at a point as CHF increased, the CHF elasticity w.r.t. cropland price turned to negative since cropland price was driven to negative due to the exogenous CHF change. However, making CHF endogenous means any change in CHF should be as a result from the mandate shock on grain and the CHF should not have a dominating impact. Thus, the CHF elasticity w.r.t. cropland price is likely to be positive. More historical data are needed for carefully calibrating the CHF elasticity w.r.t. cropland price and for developing an endogenous mechanism in the model.

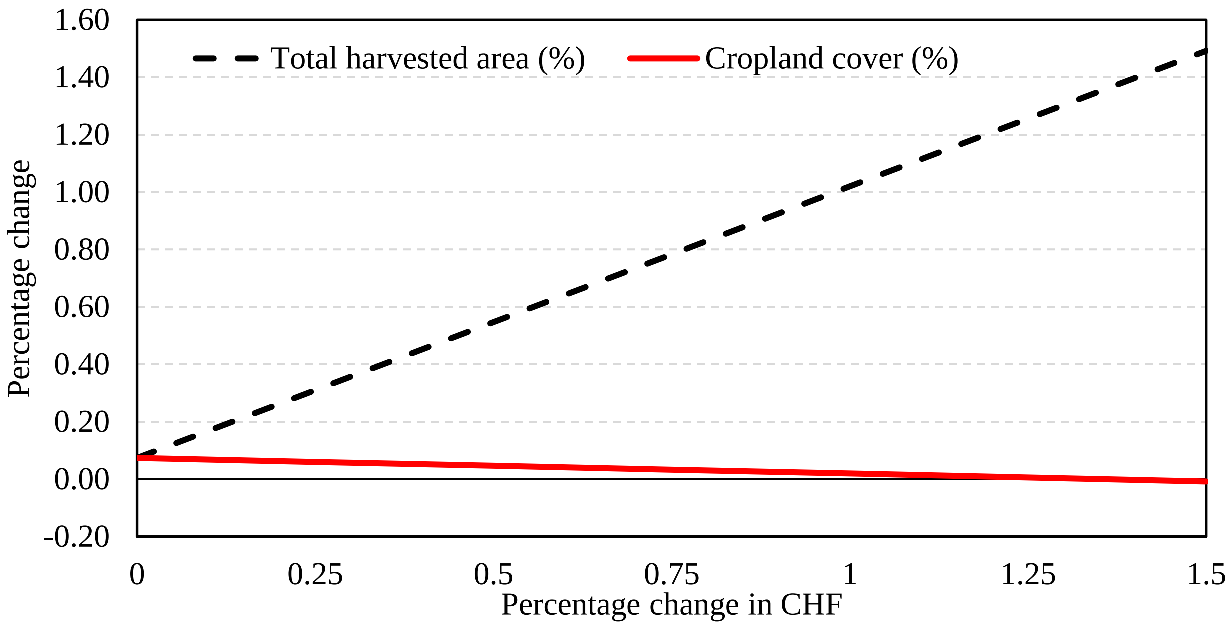


Fig. 4 Percentage changes in total harvested area and cropland cover for the USA in experiment 5

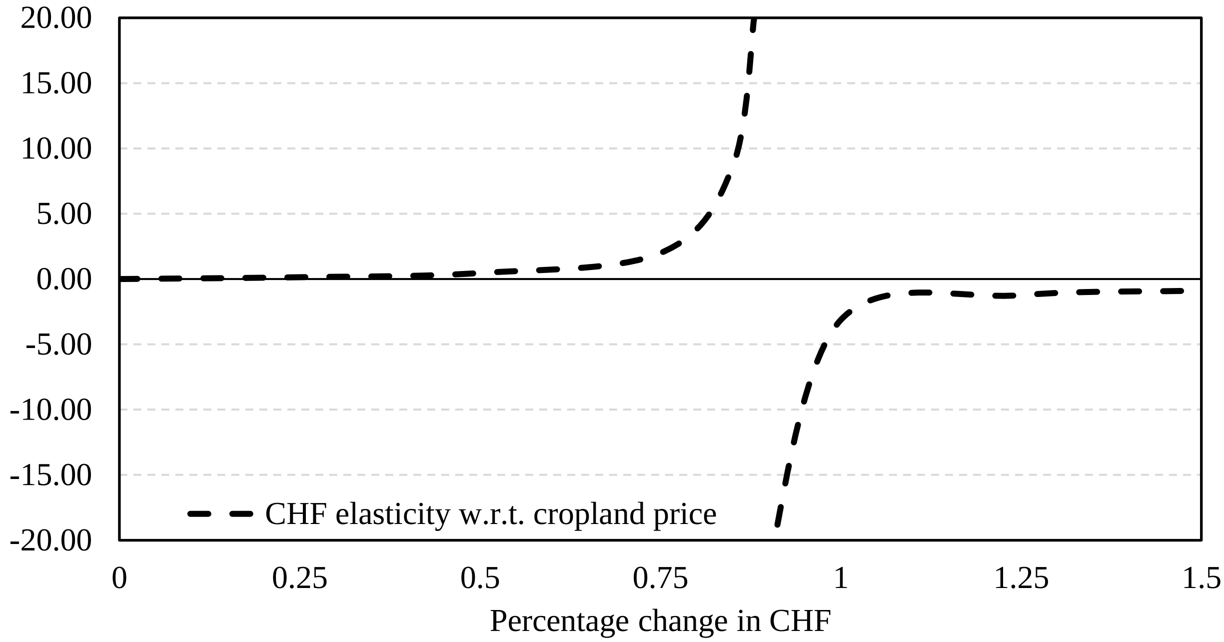


Fig. 5 CHF elasticity with respect to cropland price for the USA in experiment 5

6. Conclusion

The constant elasticity of transformation (CET) functional form has been widely used in CGE models for handling land heterogeneity. However, the CET approach cannot provide traceable land use change results since land productivity changes due to land transformation are implicitly adjusted by shifting effective land supply so that results are “effective land” rather than physical land. In this study, we proposed a framework in which land transformation was physically modeled using the additive CET (ACET) approach while land productivity changes due to transformation were adjusted from land demand in production. We disaggregated land productivity changes technical shifters from CET using ACET. We demonstrated that implementing a same land productivity change technical shifter from either land supply side or land demand side provided identical results in non-land market equilibrium.

For the purpose of this study, we build a simple CGE model and design experiments to comparing CET with ACET and to testing the sensitivity of two new margin responses including land productivity response due to transformation and the multiple cropping and unused land response. We demonstrated that the ACET approach plus the land productivity adjustments provide a promising alternative to the CET approach in modeling land supply in CGE model, despite that more careful studies are necessary for calibrating parameters for important responses.

The approach proposed in this study may have the following implications:

(1) It helps understand the assumptions behind CET and provided important implications on parameters calibration.
(2) The approach may have important implication on the Armington structure where CES was used for aggregating homogeneous goods. That is, the Armington structure may be providing “effective” trade volumes where commodity quality plays an important role.
(3) The approach may be applied for studying labor issues whereas physical labor supply is needed. And the employment rate is similar to crop harvest frequency (CHF) that they may shift factor supply.
(4) The approach narrows the gap between top-down models and bottom-up models. This extends the capability of CGE models by linking the CGE world to the physical world.

References

Aguiar, A., Narayanan, B., McDougall, R., 2016. An overview of the GTAP 9 data base. Journal of Global Economic Analysis 1, 181-208.

Ahammad, H., Mi, R., 2005. Land Use Change Modeling in GTEM Accounting for Forest Sinks. Australian Bureau of Agricultural and resource Economics.

Al-Riffai, P., Dimaranan, B., Laborde, D., 2010. Global trade and environmental impact study of the EU biofuels mandate. IFPRI Washington, DC.

Arrow, K.J., Chenery, H.B., Minhas, B.S., Solow, R.M., 1961. Capital-labor substitution and economic efficiency. The Review of Economics and Statistics, 225-250.

Burfisher, M.E., 2011. Introduction to Computable General Equilibrium Models. Cambridge University Press.

Dixon, P.B., Rimmer, M.T., 2003. A New Specification of Labour Supply in the MONASH Model with an Illustrative Application. Australian Economic Review 36, 22-40.

Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., 2014. Land use representation in a global CGE model for long-term simulation: CET vs. logit functions. Food Security 6, 685-699.

Giesecke, J., Tran, N.H., Corong, E., Jaffee, S., 2013. Rice Land Designation Policy in Vietnam and the Implications of Policy Reform for Food Security and Economic Welfare. The Journal of Development Studies 49, 1202-1218.

Golub, A., Hertel, T.W., Sohngen, B., 2009. Land use modelling in a recursively dynamic GTAP framework, Economic Analysis of Land Use in Global Climate Change Policy, p. 235.

Golub, A., Hertel, T.W., Taheripour, F., Tyner, W.E., 2010. Chapter 6 Modeling Biofuels Policies in General Equilibrium: Insights, Pitfalls, and Opportunities. New Developments in Computable General Equilibrium Analysis for Trade Policy (Frontiers of Economics and Globalization, Volume 7) Emerald Group Publishing Limited 7, 153-187.

Gurgel, A., Reilly, J., Paltsev, S., 2007. Potential Land Use Implications of a Global Biofuels Industry. Journal of Agricultural & Food Industrial Organization 5, 1202-1202.

Hertel, T.W., Golub, A.A., Jones, A.D., O'Hare, M., Plevin, R.J., Kammen, D.M., 2010. Effects of US maize ethanol on global land use and greenhouse gas emissions: estimating market-mediated responses. BioScience 60, 223-231.

Hertel, T.W., Lee, H.-L., Rose, S., Sohngen, B., 2009a. Modelling land use related greenhouse gas sources and sinks and their mitigation potential.

Hertel, T.W., Rose, S., Tol, R.S.J., 2009b. Land use in computable general equilibrium models: An overview.

Hertel, T.W., Tsigas, M.E., 1996. Structure of GTAP, in: Hertel, T.W. (Ed.), Global Trade Analysis: Modeling and Applications. Cambridge University Press, Cambridge, pp. 13-73.

Huff, K., Hertel, T., 2000. Decomposing welfare changes in the GTAP model.

Keeney, R., Hertel, T.W., 2009. The Indirect Land Use Impacts of United States Biofuel Policies: The Importance of Acreage, Yield, and Bilateral Trade Responses. American Journal of Agricultural Economics 91, 895-909.

Mariano, M.J.M., Giesecke, J.A., 2014. The macroeconomic and food security implications of price interventions in the Philippine rice market. Economic Modelling 37, 350-361.

Peña-Lévano, L., Taheripour, F., Tyner, W., 2015. Development of the GTAP Land Use Data Base for 2011. GTAP Research Memorandum.

Powell, A.A., Gruen, F., 1968. The constant elasticity of transformation production frontier and linear supply system. International Economic Review 9, 315-328.

Sands, R.D., Leimbach, M., 2003. Modeling Agriculture and Land Use in an Integrated Assessment Framework. Climatic Change 56, 185-210.
Taheripour, F., Cui, H., Tyner, W.E., 2016. An Exploration of Agricultural Land Use Change at the Intensive and Extensive Margins: Implications for Biofuels Induced Land Use Change Modeling.
Taheripour, F., Tyner, W.E., 2013. Biofuels and land use change: Applying recent evidence to model estimates. Applied Sciences 3, 14-38.
Taheripour, F., Zhuang, Q., Tyner, W.E., Lu, X., 2012. Biofuels, cropland expansion, and the extensive margin. Energy, Sustainability and Society 2, 25.
Tyner, W.E., Taheripour, F., Zhuang, Q., Birur, D., Baldos, U., 2010. Land use changes and consequent CO2 emissions due to US corn ethanol production: A comprehensive analysis. Department of Agricultural Economics, Purdue University.
Valin, H., Havlík, P., Forsell, N., Frank, S., Mosnier, A., Peters, D., Hamelinck, C., Spöttle, M., van den Berg, M., 2013. Description of the GLOBIOM (IIASA) Model and Comparison with the MIRAGE-BioF (IFPRI) Model. Crops 8, 3.1.
van der Mensbrugghe, D., 2010. The environmental impact and sustainability applied general equilibrium (ENVISAGE) model. The World Bank, January.
van der Mensbrugghe, D., Peters, J., 2016. Volume preserving CES and CET formulations, 2016 GTAP Conference Paper. GTAP Resource.
van Meijl, H., van Rheenen, T., Tabeau, A., Eickhout, B., 2006. The impact of different policy environments on agricultural land use in Europe. Agriculture, Ecosystems & Environment 114, 21-38.
Verburg, R., Stehfest, E., Woltjer, G., Eickhout, B., 2009. The effect of agricultural trade liberalisation on land-use related greenhouse gas emissions. Global Environmental Change 19, 434-446.
Wise, M., Calvin, K., Kyle, P., Luckow, P., Edmonds, J., 2014. Economic and physical modeling of land use in GCAM 3.0 and an application to agricultural productivity, land, and terrestrial carbon. Climate Change Economics 5, 1450003.

Appendix A

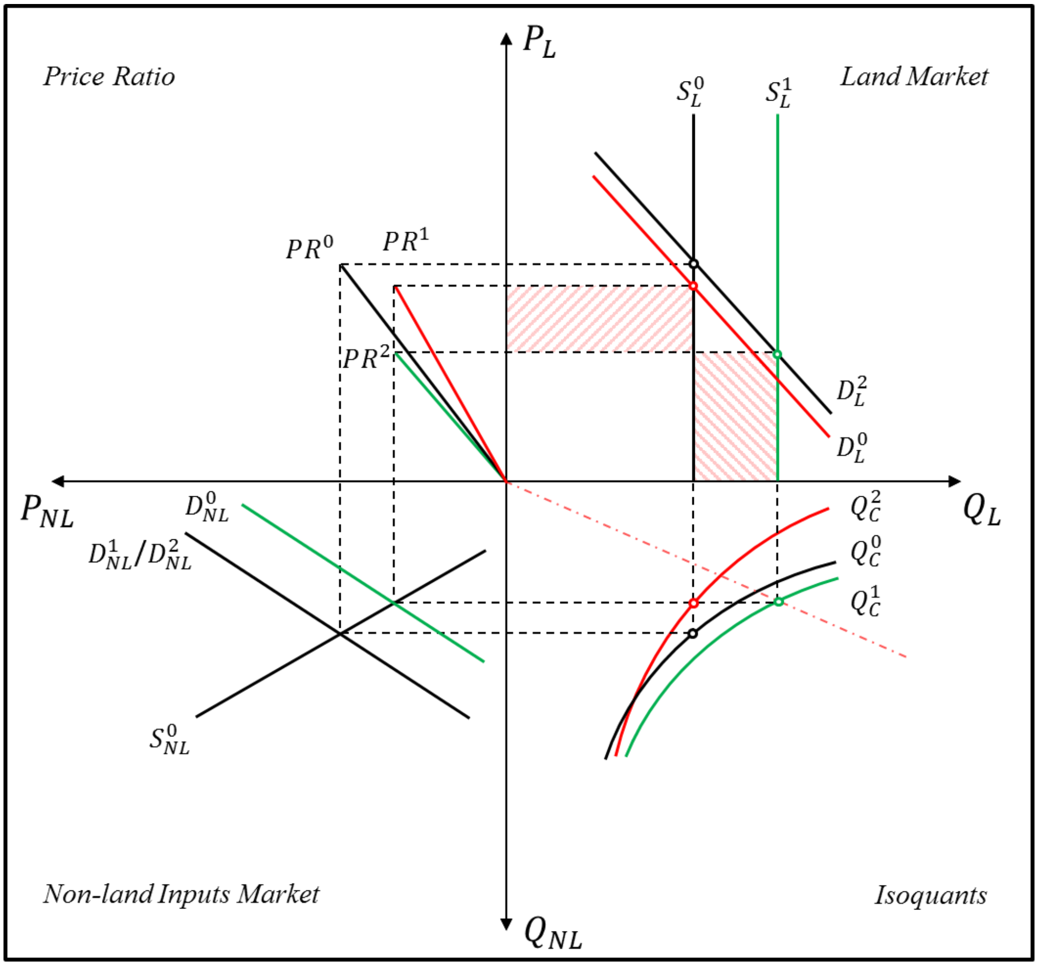


Fig. A1 Two approaches of implementing a land productivity change in CGE models (the case of decreasing land demand).

Table A1 Mapping between GTAP data base to the data base in this study

NO.	GTAP data base	Sectors in this study	NO.	GTAP data base	Sectors in this study
1	pdr	Other crops	30	lum	Manufacture
2	wht	Other crops	31	ppp	Manufacture
3	gro	Grain	32	p_c	Manufacture
4	v_f	Other crops	33	crp	Manufacture
5	osd	Other crops	34	nmm	Manufacture
6	c_b	Other crops	35	i_s	Manufacture
7	pfb	Other crops	36	nfm	Manufacture
8	ocr	Other crops	37	fmp	Manufacture
9	ctl	Livestock	38	mvh	Manufacture
10	oap	Food	39	otn	Manufacture
11	rmk	Livestock	40	ele	Manufacture
12	wol	Livestock	41	ome	Manufacture
13	frs	Forestry	42	omf	Manufacture
14	fsh	Food	43	ely	Manufacture
15	coa	Manufacture	44	gdt	Manufacture
16	oil	Manufacture	45	wtr	Service
17	gas	Manufacture	46	cns	Service
18	omn	Manufacture	47	trd	Service
19	cmt	Food	48	otp	Service
20	omt	Food	49	wtp	Service
21	vol	Food	50	atp	Service
22	mil	Food	51	cmn	Service
23	pcr	Food	52	ofi	Service
24	sgr	Food	53	isr	Service
25	ofd	Food	54	obs	Service
26	b_t	Food	55	ros	Service
27	tex	Manufacture	56	osg	Service
28	wap	Manufacture	57	dwe	Service
29	lea	Manufacture			

Note: See GTAP data base documentation from Aguiar et al. (2016) for detailed descriptions.

Table A2 Simulation results from experiments 1-3

Simulation results		Experiment 1			Experiment 2			Experiment 3		
Major indicators	Sector	USA	EU	ROW	USA	EU	ROW	USA	EU	ROW
Land use change (%)	Grain	1.625	-0.007	0.032	1.702	0.001	0.028	1.795	-0.004	0.031
	Other crops	-0.705	0.005	-0.002	-0.514	0.004	-0.004	-0.539	0.009	-0.003
	Livestock	-0.085	-0.006	-0.004	-0.026	-0.003	-0.001	-0.026	-0.004	-0.001
	Forestry	-0.030	-0.004	-0.003	-0.018	-0.002	-0.001	-0.022	-0.003	-0.002
Land rent change (%)	Grain	4.747	0.418	0.266	4.028	0.246	0.176	4.572	0.415	0.268
	Other crops	1.556	0.435	0.221	1.017	0.250	0.134	1.387	0.431	0.222
	Livestock	-2.069	-0.001	0.006	-2.298	-0.041	-0.027	-2.127	-0.004	0.003
	Forestry	0.122	0.037	0.033	0.060	0.022	0.021	0.113	0.036	0.033
Production output change (%)	Grain	1.787	0.006	0.043	1.840	0.009	0.035	1.787	0.006	0.043
	Other crops	-0.642	0.017	0.011	-0.472	0.011	0.004	-0.642	0.017	0.011
	Livestock	-0.377	-0.005	-0.002	-0.352	-0.009	-0.004	-0.377	-0.005	-0.002
	Forestry	-0.021	-0.001	0.001	-0.014	0.000	0.001	-0.021	-0.001	0.001
	Food	0.142	-0.011	-0.026	0.143	-0.014	-0.026	0.142	-0.011	-0.026
	Manufacture	-0.008	0.001	0.002	-0.012	0.002	0.003	-0.008	0.001	0.002
	Service	-0.001	0.000	0.000	-0.002	0.000	0.000	-0.001	0.000	0.000
Market price change (%)	Grain	0.669	0.049	0.046	0.570	0.028	0.029	0.669	0.049	0.046
	Other crops	0.267	0.044	0.050	0.177	0.024	0.029	0.267	0.044	0.050
	Livestock	0.074	0.006	0.006	0.021	-0.001	-0.003	0.074	0.006	0.006
	Forestry	0.033	0.014	0.011	0.015	0.007	0.006	0.033	0.014	0.011
	Food	-0.202	0.001	0.010	-0.210	-0.001	0.004	-0.202	0.001	0.010
	Manufacture	0.000	-0.005	-0.005	0.003	-0.004	-0.004	0.000	-0.005	-0.005
	Service	0.000	-0.005	-0.006	0.003	-0.005	-0.005	0.000	-0.005	-0.006
Yield change (%)	Grain	0.162	0.013	0.011	0.138	0.008	0.007	-0.008	0.010	0.012
Yield elasticity	Grain	0.242	0.271	0.241	0.242	0.286	0.252	-0.012	0.199	0.268
Total EV (2011 MM $)		138	-58	-280	169	-47	-231	138	-58	-280
EV-Endowments		0	0	0	80	1	-7	85	2	-3
EV-Allocative efficiency		-81	-11	-108	-116	-2	-65	-99	-11	-107
EV-Terms of trade		204	-39	-165	168	-38	-130	204	-39	-165
EV-Capital goods and saving		15	-8	-7	37	-8	-29	15	-8	-7
EV-Technology		0	0	0	0	0	0	-67	-1	3
Harvested area (Thousand ha)	Grain	604	-2	79	633	0	68	667	-1	76
	Other crops	-736	5	-17	-536	4	-35	-563	8	-28
	Total area	-131	3	62	97	4	34	105	7	48
Land cover (Thousand ha)	Cropland	23	4	14	106	4	36	114	7	51
	Pasture	-214	-4	-112	-66	-2	-21	-66	-3	-24
	Forest	-66	-6	-30	-39	-2	-15	-48	-4	-27
Land cover discrepancy		-257	-6	-128	0	0	0	0	0	0
CHF change		Unknown			0	0	0	0	0	0

Table A3 Simulation results from experiment 5

USA	Percentage change in CHF						
	0	0.25	0.5	0.75	1	1.25	1.5
Grain area (%)	1.80	1.89	1.98	2.08	2.17	2.27	2.36
Other crops area (%)	-0.54	-0.25	0.04	0.32	0.61	0.90	1.18
Total harvested area (%)	0.07	0.31	0.55	0.78	1.02	1.26	1.49
Cropland cover (%)	0.07	0.06	0.05	0.03	0.02	0.01	-0.01
Pasture (%)	-0.03	-0.02	-0.02	-0.02	-0.02	-0.01	-0.01
Forest (%)	-0.02	-0.02	-0.01	0.00	0.01	0.01	0.02
Cropland price (%)	2.48	1.78	1.08	0.38	-0.32	-1.01	-1.70
Grain output (%)	1.79	1.86	1.94	2.01	2.09	2.16	2.24
Grain price (%)	0.67	0.51	0.35	0.19	0.03	-0.12	-0.28
CHF elasticity w.r.t. cropland price	0.00	0.14	0.47	1.99	-3.13	-1.24	-0.88

Appendix B

The derivation in this approach has two stages in which the first stage is identical to the standard CET land supply, and the second stage endogenizes the technical shifter(s) subject to a volume-preserving constraint.

1. Stage one, standard CET land supply

We start from the standard CET land supply derivation. The objective is to maximize revenue, π, in equation (1.1) subject to the CET function in equation (1.2). P_i is the price of land i after transformation and X_i is the supply of land i. Y is total land area.

$$\max_{X_i} \ \pi = \sum_i P_i X_i \tag{1.1}$$

$$s.t. \qquad Y = \alpha\left[\sum_i \beta_i \left(\lambda_i X_i\right)^v\right]^{\frac{1}{v}} \tag{1.2}$$

$$v = \frac{\omega + 1}{\omega} \tag{1.3}$$

v is the CET exponent and ω is the absolute value of the elasticity of transformation. α is the neutral technical shifter and λ_i is the biased technical shifter for the land i. β_i are the CET coefficients which are typically benchmarked using the base year data. Solving the optimization program, the land supply function can be derived as

$$X_i = \frac{Y}{\alpha} \cdot \left(\frac{P_i}{\beta_i}\right)^{\omega} \cdot \lambda_i^{-1-\omega} \cdot \left[\sum_j \beta_j^{-\omega} \left(\frac{P_j}{\lambda_j}\right)^{1+\omega}\right]^{-\frac{\omega}{1+\omega}} \tag{1.4}$$

According to the zero-profit condition,

$$PY = \sum_i P_i X_i \tag{1.5}$$

Substituting (1.4) into (1.5), the price of Y can be derived,

$$P = \frac{1}{\alpha}\left[\sum_i \beta_i^{-\omega}\left(\frac{P_i}{\lambda_i}\right)^{1+\omega}\right]^{\frac{1}{1+\omega}} \tag{1.6}$$

Substituting (1.6) into (1.4), supply function can be simplified as

$$X_i = Y \cdot \left(\frac{P_i}{P}\right)^{\omega} \cdot \beta_i^{-\omega} \cdot (\lambda_i \alpha)^{-\omega-1} \tag{1.7}$$

Equation (1.6) provides the price linkage which implies the zero-profit condition. Equation (1.7) is the supply function from the standard CET function. It consists of effects from expansion (Y), substitution ($(P_i/P)^{\omega}$), and technical shift ($(\lambda_i\alpha)^{-\omega-1}$). Note that if λ_i are the same across i, λ_i and α will be indifferent in function.

2. **Stage two, volume-preserving condition**

In the stage two, we simply add the volume-preserving constraint to equation (1.7) to endogenize α and/or λ_i. However, before proceeding, an important question to discuss is the difference between the crop harvested area and physical land cover. When land is transformed between forest, pasture, and cropland covers, the land conversion volume should be preserved with no doubt (e.g., the area decrease in forest cover should equal the area increase in pasture cover). The story will be different when transforming forest or pasture land covers to crop harvested area since usually there are multiple cropping practices and unused cropland, both of which lead to a gap between cropland cover and crop harvested area. To model the land transition clearly and consistently, in the present study, crop harvested areas are designed to be supplied by cropland cover through introduced efficient variables (φ and/or ι_i). The specific crop intensity indices (SCII) is represented in ι_i. Those efficient variables are implemented from the volume-preserving condition (equation (1.8)) as they share a similar definition with a macro index, CHF.

$$Y = \frac{1}{\varphi} \cdot \left(\sum_i \frac{X_i}{\iota_i}\right) \tag{1.8}$$

When ι_i for each i is equal to 1, η is the standard CHF, which is the ratio of total crop harvested area over cropland cover. When η is equal to 1, ι_i are cropland-biased CHFs or specific crop intensities. In our study, we only focus on η due to the limited information on the specific crop intensity so that ι_i will be set to 1. However, ι_i makes possible distinguishing crops by their abilities of multiple cropping or use of unused cropland in future studies. In equation (1.8), both η and ι_i will be set to 1 if the land transformation is among land covers or among harvested area. Only in the case of transforming from cropland cover to harvested area, φ comes into play.

In this study, we address the non-preserving discrepancy only using the neutral technical shift (α), but leave the possibility of investigating land biased technical shifters (λ_i) in future studies. Thus, to endogenously determine α, we substitute (1.4) into (1.8),

$$\alpha = \frac{1}{\varphi} \cdot \left[\sum_i \frac{1}{\iota_i}\left(\frac{P_i}{\beta_i}\right)^{\omega} \lambda_i^{-1-\omega}\right] \cdot \left[\sum_i \beta_i^{-\omega}\left(\frac{P_i}{\lambda_i}\right)^{1+\omega}\right]^{-\frac{\omega}{1+\omega}} \tag{1.9}$$

Assuming λ_i to be exogenous (equal to 1), the equation (1.9) can be directly used as an equation in conjunction with equations (1.6) and (1.7) to preserve additivity. Alternatively, we can update the new volume-preserving land supply function by substituting (1.9) into (1.7),

$$X_i = \frac{P_i^{\omega} \beta_i^{-\omega} \lambda_i^{-1-\omega}}{\sum_j \iota_i^{-1} P_j^{\omega} \beta_j^{-\omega} \cdot \lambda_j^{-1-\omega}} \cdot \varphi \cdot Y \quad (1.10)$$

Thus, equation (1.10) becomes the volume-preserving land supply function. In equation (1.10), it is apparent that if η and ι_i are equal to 1, the sum of X_i amounts to Y. Note that we split the derivation into two stages to make it more communicable. But essentially, the land supply in equation (1.10) can be achieved by solving a system of equations that consist of the first-order conditions (FOC) in the stage-one maximization problem and volume-preserving condition in equation (1.8). The two-stage approach provides an intermediate equation of α, which helps understand the mechanism from the perspective of standard CET. Equation (1.10) is equivalent to the standard CET supply in equation (1.7) plus the endogenous technical shifters in equation (1.9). Equation (1.10) can be interpreted as a new functional form, as in van der Mensbrugghe and Peters (2016), which transforms land based on volume rather than value. However, from the perspective of the standard CET, how to explain α or λ_i is critical. As explained in Fig.1, the extent of the land transformation discrepancy depends on the curvature of the production frontier, the shock level, and the initial land or rental distribution. Using an example of converting forest to cropland in which the regional forest land price is smaller than cropland price and the shock is to increase cropland, in this case, the discrepancy is always negative (land loss). This is because the standard CET transforms land by value, thus the decrease in the lower-price forest land has to be larger than the increase in the higher-price cropland to maintain the value balance. As mentioned earlier, Golub et al. (2009) interpreted the transformed lands on the standard CET frontier as the effective lands or productivity-weighted lands because the land rental implies the land productivity. However, the productivity-weighted adjustment may not explain all the discrepancies given that technical changes and other non-market impacts may accompany land transformation. Also, any adjustments on land volume-preserving and productivity should be inside the model. Therefore, in the ACET approach, we endogenize α to address the discrepancy but provide land productivity adjustment from the crop production side. Thus, in the above example, the negative discrepancy entails a negative α, one effect of which is to positively scale up transformed land to preserve additivity. We concentrate on α in this study, but it is certain that λ_i can provide more flexibility in land transformation subject to more information and research.

3. Log-differentiation

The log-differentiated forms are used in GEMPACK-based CGE models. Throughout this study, hat (^) denotes proportional change ($\hat{X} = \Delta X / X$).

Denote s_i as ι_i adjusted volume shares,

$$s_i = \frac{X_i / \iota_i}{\sum_j X_j / \iota_j} \quad (1.11)$$

and denote θ_i as value shares,

$$\theta_i = \frac{P_i X_i}{\sum_j P_j X_j} \quad (1.12)$$

Equations (1.13) - (1.15) are derived by log-differentiating (1.6), (1.7), and (1.9), respectively.

$$\hat{P} = \sum_j \theta_j (\hat{P}_j - \hat{\lambda}_j) - \hat{\alpha} \tag{1.13}$$

$$\hat{X}_i = \hat{Y} + \omega[\hat{P}_i - \hat{P}] - (1+\omega)\hat{\lambda}_i - (1+\omega)\hat{\alpha} \tag{1.14}$$

$$\hat{\alpha} = \sum_i [\omega(s_i - \theta_i)\hat{P}_i] - \sum_i [(1+\omega)s_i\hat{\lambda}_i - \omega\theta_i\hat{\lambda}_i] - \sum_i (s_i\hat{\iota}_i) - \hat{\varphi} \tag{1.15}$$

One advantage of using (1.7) and (1.9) rather than (1.10) is that $\hat{\alpha}$ is easy to be added on the basis of the standard CET land supply, and it permits tracking to what extent the discrepancy had been addressed by $\hat{\alpha}$. If setting $\hat{\iota}_i$, $\hat{\varphi}$ and $\hat{\lambda}_i$ to zero, and substituting (1.15) into (1.14), the supply function derived will be identical to the formulas derived by van der Mensbrugghe and Peters (2016) from the utility maximization perspective.

Appendix C

```
Equation EV_DECOMPOSITION
# decomposition of Equivalent Variation #
(all,r,REG)
EV_ALT(r)
= [0.01 * EVSCALFACT(r)] * [
+ sum(i, ENDW_COMM, VOA(i,r) * [qo(i,r) - pop(r)]) - VDEP(r) * [kb(r) - pop(r)]
+ sum(i, ENDWS_COMM, VOM(i,r) * pm(i,r))
- sum(i, ENDWS_COMM, sum(j,ALL_INDS, VFM(i,j,r) * pmes(i,j,r)))
+ sum(i,NSAV_COMM, PTAX(i,r) * [qo(i,r) - pop(r)])
+ sum(i,ENDW_COMM, sum(j,ALL_INDS, ETAX(i,j,r) * [qfe(i,j,r) - pop(r)]))
+ sum(j,ALL_INDS, sum(i,TRAD_COMM, [IFTAX(i,j,r) ] * [qfm(i,j,r) - pop(r)]))
+ sum(j,ALL_INDS, sum(i,TRAD_COMM, [DFTAX(i,j,r) ] * [qfd(i,j,r) - pop(r)]))
+ sum(i,TRAD_COMM, [IPTAX(i,r) ] * [qpm(i,r) - pop(r)])
+ sum(i,TRAD_COMM, [DPTAX(i,r) ] * [qpd(i,r) - pop(r)])
+ sum(i,TRAD_COMM, [IGTAX(i,r) ] * [qgm(i,r) - pop(r)])
+ sum(i,TRAD_COMM, [DGTAX(i,r) ] * [qgd(i,r) - pop(r)])
+ sum(i,TRAD_COMM, sum(s,REG, XTAXD(i,r,s) * [qxs(i,r,s) - pop(r)]))
+ sum(i,TRAD_COMM, sum(s,REG, MTAX(i,s,r) * [qxs(i,s,r) - pop(r)]))
+ sum(i,ALL_INDS,VOA(i,r) * ao(i,r))
+ sum(j,ALL_INDS, sum(i,FIRM_COMM, VFA(i,j,r) * af(i,j,r)))
+ sum(m,MARG_COMM, sum(i,TRAD_COMM, sum(s,REG, VTMFSD(m,i,s,r) * atmfsd(m,i,s,r))))
+ sum(i,TRAD_COMM, sum(s,REG, VIMS(i,s,r) * ams(i,s,r)))
+ sum(i,TRAD_COMM, sum(s,REG, VXWD(i,r,s) * pfob(i,r,s)))
+ sum(m,MARG_COMM, VST(m,r) * pm(m,r))
- sum(i,TRAD_COMM, sum(s,REG, VXWD(i,s,r) * pfob(i,s,r)))
- sum(m,MARG_COMM, VTMD(m,r) * pt(m))
+ NETINV(r) * pcgds(r) - SAVE(r) * psave(r)]
+ 0.01 * INCOMEEV(r) * pop(r);


Equation CONT_EV_endwr
# contribution to regional EV of changes in all ENDW_COMM #
(all,r,REG)
CNTendwr(r)
= [0.01 * EVSCALFACT(r)] * [
+ sum(i, ENDW_COMM, VOA(i,r) * [qo(i,r) - pop(r)]) - VDEP(r) * [kb(r) - pop(r)]
+ sum(i, ENDWS_COMM, VOM(i,r) * pm(i,r))
- sum(i, ENDWS_COMM, sum(j,ALL_INDS, VFM(i,j,r) * pmes(i,j,r)))]];

Equation CONT_EV_alleffr
# total contribution to regional EV of allocative effects #
(all,r,REG)
CNTalleffr(r)
= [0.01 * EVSCALFACT(r)] * [
+ sum(i,NSAV_COMM, PTAX(i,r) * [qo(i,r) - pop(r)])
+ sum(i,ENDW_COMM, sum(j,ALL_INDS, ETAX(i,j,r) * [qfe(i,j,r) - pop(r)]))
+ sum(j,ALL_INDS, sum(i,TRAD_COMM, [IFTAX(i,j,r) ] * [qfm(i,j,r) - pop(r)]))
+ sum(j,ALL_INDS, sum(i,TRAD_COMM, [DFTAX(i,j,r) ] * [qfd(i,j,r) - pop(r)]))
+ sum(i,TRAD_COMM, [IPTAX(i,r) ] * [qpm(i,r) - pop(r)])
+ sum(i,TRAD_COMM, [DPTAX(i,r) ] * [qpd(i,r) - pop(r)])
+ sum(i,TRAD_COMM, [IGTAX(i,r) ] * [qgm(i,r) - pop(r)])
+ sum(i,TRAD_COMM, [DGTAX(i,r) ] * [qgd(i,r) - pop(r)])
```

```
+ sum(i,TRAD_COMM, sum(s,REG, XTAXD(i,r,s) * [qxs(i,r,s) - pop(r)]))
+ sum(i,TRAD_COMM, sum(s,REG, MTAX(i,s,r) * [qxs(i,s,r) - pop(r)]))];


Equation CONT_EV_techr
# contribution to regional EV of all technical change #
(all,r,REG)
CNTtechr(r)
= [0.01 * EVSCALFACT(r)] * [
+ sum(i,ALL_INDS, VOA(i,r) * ao(i,r))+
+ sum(j,ALL_INDS, sum(i,FIRM_COMM, VFA(i,j,r) * af(i,j,r)))
+ sum(m,MARG_COMM, sum(i,TRAD_COMM, sum(s,REG, VTMFSD(m,i,s,r) * atmfsd(m,i,s,r))))
+ sum(i,TRAD_COMM, sum(s,REG, VIMS(i,s,r) * ams(i,s,r)))];


Equation CONT_EV_totr
# contribution to regional EV of changes in its terms of trade #
(all,r,REG)
CNTtotr(r)
= [0.01 * EVSCALFACT(r)] * [
+ sum(i,TRAD_COMM, sum(s,REG, VXWD(i,r,s) * pfob(i,r,s)))
+ sum(m,MARG_COMM, VST(m,r) * pm(m,r))
- sum(i,TRAD_COMM, sum(s,REG, VXWD(i,s,r) * pfob(i,s,r)))
- sum(m,MARG_COMM, VTMD(m,r) * pt(m))];

Equation CNT_EV_cgdsr
# contribution to regional EV of changes in the price of cgds #
(all,r,REG)
CNTcgdsr(r)
= [0.01 * EVSCALFACT(r)] * [NETINV(r) * pcgds(r) - SAVE(r) * psave(r)];
```