Land Allocation and the Carbon Consequences of Biofuel Expansion

Abstract

Regulators count the carbon released when biofuel demand pulls new land into crops, but the estimates they use differ widely across economic models. In this paper, we ask how much of that difference comes from how the models allocate land. We place five common specifications—Fréchet heterogeneous land, CET, additive CET, Classical Logit, and Entropy Logit—in a unified global general equilibrium framework, with the same benchmark data and land parameters, and raise U.S. biofuel production 8.7-fold. We find similar output responses across all five specifications, but carbon losses differ by more than a factor of two among the four that allocate physical hectares. Under Fréchet, expansion draws in land that is less suited to the crop, so it requires more land than additive CET for the same output. CET does not conserve physical area, so its land changes do not translate directly into carbon. Logit responds to return levels rather than percentage changes, affecting how land shifts across crops. The dependence of carbon consequences on land allocation thus cautions against basing regulation on a single model specification.

Keywords: Land allocation, Biofuels, Indirect land-use change, General equilibrium, Agricultural trade, Productivity selection
JEL: C68, F18, Q15, Q17, Q42, Q54

1. Introduction

When biofuel demand raises the need for feedstocks, farmers can respond by using more inputs on existing cropland, switching land across crops, or bringing pasture, forest, and other land into cultivation. Trade spreads these adjustments across countries as production, prices, and land use respond together. General equilibrium models capture these linked responses, but their carbon implications depend critically on how changes in land returns translate into physical land use. The same increase in feedstock supply can therefore require very different amounts and sources of new cropland, with different carbon consequences (Searchinger et al., 2008; Hertel et al., 2010).

These carbon consequences matter directly for regulation. For example, EPA includes significant indirect emissions in its lifecycle analysis under the Renewable Fuel Standard, California's Low Carbon Fuel Standard incorporates indirect land-use change into fuel carbon intensities, and ICAO includes induced land-use change in its accounting for CORSIA-eligible aviation fuels (U.S. Environmental Protection Agency, 2023; California Air Resources Board; International Civil Aviation Organization, 2025). Because these emissions cannot be observed directly, their measurement requires a counterfactual: how does land use change when demand for feedstocks increases? Estimating this counterfactual requires an economic model, and the resulting carbon estimate depends on how the model specifies production, trade and land allocation.

Over the past two decades, estimates of land-use emissions from biofuels have differed substantially. Hertel et al. (2010) estimate land-use emissions of about 27 gCO_2e/MJ for U.S. maize ethanol, while Taheripour et al. (2017) obtain 12 gCO_2e/MJ after changes to the economic data, parameters and treatment of land intensification. EPA's model comparison likewise finds wide variation and attributes it to differences in trade, food and feed substitution, land conversion and land classification (U.S. Environmental Protection Agency, 2023). Because these comparisons vary several features at once, they cannot tell us how much each one matters. In this paper, we isolate the contribution of the land-allocation specification by holding the rest of the economic model fixed.

Land specifications can reproduce the same benchmark acreage and land payments while imposing different restrictions on how productive new land is and how land responds to changes in relative returns. Since these restrictions are determined by the choice of specification before any policy is simulated, holding the benchmark and the rest of the model fixed allows us to compare how they affect the counterfactual.

We place five specifications—Fréchet heterogeneous land, constant elasticity of transformation (CET), additive CET (ACET), Classical Logit and Entropy Logit—in the same multi-country general equilibrium model, holding fixed the 2001 benchmark data, non-land production structure, preferences and trade. Land is allocated first among cropland, pasture, managed forest and idle land, and then among crops. Fréchet, CET and ACET share the same land-response coefficients, and we calibrate Logit to approximate their local responses.[1] Following Hertel et al. (2010), we raise annual U.S. biofuel production from 6.55 to 56.7 billion liters, about 8.7 times its benchmark level, and ask how land use and carbon emissions differ across specifications.

We find that the choice of land specification changes the carbon estimate by more than a factor of two, even though feedstock output responds similarly across specifications. Among the four specifications that allocate physical hectares, land-use carbon losses range from 2,423 $MtCO_2e$ under ACET to 5,287 $MtCO_2e$ under Fréchet, while all five

[1]The common coefficients govern percentage responses to relative returns. Local land and output-supply elasticities also depend on aggregation weights and productivity selection. The Logit match is approximate because one scale parameter applies to land uses with different initial returns. See also Section 4.

specifications raise U.S. coarse-grains output by 30.7 to 33.4 percent. We use this unified general equilibrium framework to show how three features of the land specifications account for these differences.

The first is the quality of land brought into use. Fréchet raises U.S. coarse-grains acreage by 32.2 percent and ACET by 17.8 percent, for output increases of 30.7 and 33.2 percent. For a given change in returns, the two move land shares by the same amount. Under Fréchet, however, expansion draws in land that is less suited to the crop, so each additional hectare adds less output. Costs rise, returns adjust, and more land is required to meet the same demand.

The second is the unit of land. CET does not conserve physical area. Its land quantities are rent-weighted indices of land services rather than hectares, and their total changes as returns change. Under CET, about two-thirds of the increase in cropland has no matching loss of pasture, forest or idle land, so its land changes do not translate directly into carbon.

The third is how land responds to returns. Fréchet, CET, and ACET respond to percentage changes in returns, while Logit responds to changes in their levels. This difference changes how land shifts across crops. Under Logit, competing crops expand in aggregate and several of their prices fall, while under the other three, competing-crop acreage declines and prices rise. Classical and Entropy Logit produce similar results, although Entropy Logit uses management labor and scales returns by management costs.

Spread over 30 years of additional fuel production, the physical-land estimates correspond to 76 to 166 gCO_2e/MJ. These are higher than the GTAP-based estimates above, partly because feedstock output rises more in our model, where all land specifications share the same treatment of by-products with no explicit substitution for feed grains, which isolates differences arising from land allocation (Section 5.3). We then examine a production subsidy, smaller expansions, and alternative land-response and trade parameters. We find that the differences across specifications are robust to these exercises. Fréchet's carbon loss is about twice ACET's when biofuel output doubles and remains about twice as large for greater expansions.

Research on biofuel-induced land-use change has studied market adjustment (Keeney and Hertel, 2009), the physical and empirical foundations of land predictions (Berry et al., 2024), and the representation of land in carbon accounting (Plevin et al., 2022). Related work models land allocation through heterogeneous productivity and comparative advantage (Costinot et al., 2016; Sotelo, 2020; Gouel and Laborde, 2021; Farrokhi and Pellegrina, 2023) or discrete choice over land uses (Lubowski et al., 2006; Carpentier and Letort, 2014). A smaller literature directly compares land-allocation specifications. Gouel et al. (2026) show that CET and Fréchet can agree on production responses while differing in acreage responses. They also compare these specifications with management-cost

Logit, estimate a nested acreage model on French farm data, and examine counterfactual acreage and yields. Fujimori et al. (2014) compare CET and Logit in a global general equilibrium model. We bring these approaches into a common general equilibrium setting, add ACET and the margin among cropland, pasture, managed forest and idle land, and trace the resulting adjustments through trade, commodity prices and land-use carbon. Our results show that land-use carbon estimates depend substantially on the land specification, cautioning against relying on a single specification when these estimates inform regulation.

2. Economic Environment

We consider a static general equilibrium economy with production, intermediate inputs, household demand, and Armington trade. Countries are indexed by n, i, agro-ecological-zone (AEZ) land sources by τ, and production sectors by j. The economy has ten sectors, including five crops, livestock, managed forestry, biofuel, other energy, and residual goods. The five crops, livestock, and managed forestry use land. We vary the land-allocation specification while holding the remaining production, demand, and trade equations fixed. Online Appendix A gives the full model, and Online Appendix F presents its level and exact-change equilibrium conditions.

2.1. Production and land returns

A land-using producer combines productive land services, labor, and an intermediate-input bundle. For each land source and use, production is

$$Q_{n,k,\tau} = (E_{n,k,\tau} L_{n,k,\tau})^{\gamma^L_{n,k}} N_{n,k,\tau}^{\gamma^N_{n,k}} M_{n,k,\tau}^{\gamma^M_{n,k}}, \qquad \gamma^L_{n,k} + \gamma^N_{n,k} + \gamma^M_{n,k} = 1, \tag{1}$$

where k denotes a land use. Under Fréchet, the same technology applies plot by plot, with $E_{n,k,\tau}$ replaced by a plot-specific draw $e_{n,k,\tau}(q)$. Under CET, L is a transformed service quantity. Under ACET and the two Logit specifications, it is physical area with fixed productivity.

The producer minimizes costs, giving the return to one unit of land as

$$R_{n,k,\tau} = E_{n,k,\tau} h_{n,k}, \qquad R_{n,k,\tau}(q) = e_{n,k,\tau}(q) h_{n,k} \quad \text{under Fréchet}, \tag{2}$$

where $h_{n,k} = p_{n,k} \hbar_{n,k}$ and $\hbar_{n,k}$ collects the wage, intermediate-price, and production-share terms. Returns therefore adjust with commodity and input prices. Non-land sectors use the corresponding Cobb–Douglas technology in labor and intermediates.

2.2. The two land-allocation margins

Each country has an endowment $\bar{L}_{n,\tau}$ of source-τ land. The upper nest allocates it among idle land, cropland, pasture, and managed forest. The lower nest allocates cropland among coarse grains, oilseeds, sugarcane, other grains, and other agriculture. For the four physical-land specifications,

$$L_{n,k,\tau} = \bar{L}_{n,\tau} s_{n,C,\tau} s_{n,k|C,\tau}, \qquad \sum_{g} s_{n,g,\tau} = 1, \qquad \sum_{k \in C} s_{n,k|C,\tau} = 1, \tag{3}$$

where C denotes cropland and g indexes upper-nest alternatives. CET uses the same nesting tree with a transformation constraint in place of physical area balance.

We characterize a generic land-allocation nest. Let r_i denote the return entering the allocation decision, s_i a physical land share, and $b_i = L_i/\bar{L}$ a normalized CET land-service quantity. Under Fréchet, r_i includes a fixed preference shifter that reconciles benchmark acreage and land-payment shares.

Fréchet heterogeneous land. Plots are assigned to the use with the highest preference-adjusted return. Each plot has a productivity draw for each land use, following a nested Fréchet distribution. At either nest the conditional share is

$$s_i = \frac{r_i^{\nu}}{\sum_j r_j^{\nu}}, \qquad \nu > 1. \tag{4}$$

The upper and lower shape parameters satisfy $1 < \nu_1 \le \nu_2$. Selection changes the average productivity of plots allocated to a use (Sotelo, 2020; Farrokhi and Pellegrina, 2023).

CET. A land manager maximizes revenue subject to a transformation frontier:

$$\max_{\{L_i\}} \sum_i r_i L_i \quad \text{subject to} \quad \left(\sum_i \beta_i L_i^{(1+\eta)/\eta} \right)^{\eta/(1+\eta)} = \bar{L}. \tag{5}$$

The first-order conditions give $b_i = \beta_i^{-\eta} (r_i/r)^{\eta}$, where $r = (\sum_j \beta_j^{-\eta} r_j^{1+\eta})^{1/(1+\eta)}$. The frontier constrains a composite of productive land services (Hertel and Tsigas, 1988).

ACET. ACET uses a proportional-return response while allocating physical area:

$$\max_{\{L_i\}} \left[\sum_i \beta_i (r_i L_i)^{\nu/(1+\nu)} \right]^{(1+\nu)/\nu} \quad \text{subject to} \quad \sum_i L_i = \bar{L}, \tag{6}$$

which implies $s_i = \beta_i^{1+\nu} r_i^{\nu} / \sum_j \beta_j^{1+\nu} r_j^{\nu}$. The fixed shifters allow benchmark shares to be matched, while the constraint preserves physical area (Zhao et al., 2020; Taheripour et al., 2020).

Classical Logit. A plot chooses the use with the highest return plus a fixed use-specific payoff and an additive extreme-value shock. The resulting shares are

$$s_i = \frac{\psi_i \exp(\alpha r_i)}{\sum_j \psi_j \exp(\alpha r_j)}, \qquad \alpha > 0, \quad \psi_i > 0, \quad \sum_i \psi_i = 1. \tag{7}$$

The inclusive return carried to the next nest is $\alpha^{-1} \log \sum_j \psi_j \exp(\alpha r_j)$. The payoff shocks disperse choices without absorbing aggregate resources (Train, 2009; Carpentier and Letort, 2014).

Entropy Logit. A manager chooses physical shares to maximize returns net of a convex management requirement:

$$\max_{\{s_i\}} \left\{ \sum_i s_i r_i - W^m \left[\bar{m} + \alpha^{-1} \sum_i s_i \log(s_i/\psi_i) \right] \right\}, \qquad \sum_i s_i = 1, \tag{8}$$

where $W^m = W_n \varpi$ is the price of a management service, and ϖ is its labor requirement. Shares have the Logit form in (7), with αr_i replaced by $\alpha r_i / W^m$. Management labor enters the resource constraint. Online Appendix A gives the complete nested specification, including the baseline management terms.

Idle land is an outside option in the upper nest. Its return is the value of the activation requirement avoided by leaving land inactive: $R_{n,0,\tau} = E_{n,0,\tau} W_n$. Activating land uses setup labor in every specification, while Entropy Logit additionally uses management labor. We map the GTAP-BIO `unmngland` cover category to the idle alternative.[2] The model uses this aggregate without distinguishing its underlying ecosystems. Section 4 describes its treatment in the carbon accounting.

2.3. *Energy, trade, and expenditure*

We combine biofuel and other energy in a CES bundle used by firms and households. For intermediate purchases, the price of this bundle is

$$P^e_{n,j} = \left[\phi^e_{n,j} P^{1-\sigma^{e,p}}_{n,\text{bio}} + (1 - \phi^e_{n,j}) P^{1-\sigma^{e,p}}_{n,\text{other}} \right]^{1/(1-\sigma^{e,p})}. \tag{9}$$

The energy bundle enters the Cobb–Douglas intermediate aggregate together with non-energy goods. Household consumption is Cobb–Douglas over non-energy categories and

[2] GTAP-BIO provides a convenient common benchmark for the model comparison (Hertel et al., 2010). Section 4 describes the data and calibration.

a CES energy bundle. A final-consumption subsidy changes the household price of biofuel to $(1-\tau^c_{n,\mathrm{bio}})P_{n,\mathrm{bio}}$ without changing firms' intermediate purchase price.

Sectoral goods are differentiated by origin (Armington, 1969). If $\kappa_{ni,j}p_{i,j}$ is the delivered price in n of goods supplied by i, the destination price index and sourcing share are

$$P_{n,j} = \left[\sum_i \zeta_{ni,j}(\kappa_{ni,j}p_{i,j})^{1-\sigma_j}\right]^{1/(1-\sigma_j)}, \tag{10}$$

$$\lambda_{ni,j} = \frac{\zeta_{ni,j}(\kappa_{ni,j}p_{i,j})^{1-\sigma_j}}{\sum_\ell \zeta_{n\ell,j}(\kappa_{n\ell,j}p_{\ell,j})^{1-\sigma_j}}. \tag{11}$$

A change in domestic supply therefore affects both domestic absorption and foreign sourcing. Land responses feed back into this system through commodity prices and intermediate demand.

2.4. Equilibrium and the policy experiment

Households receive wages, net land revenue, and a benchmark-consistent net transfer D_n, with $\sum_n D_n = 0$. Subsidies are financed by lump-sum charges. For the final-consumption subsidy on Biofuel, $T^c_n = \tau^c_{n,\mathrm{bio}}P_{n,\mathrm{bio}}C_{n,\mathrm{bio}}$. Their budget is

$$P^C_n C_n = W_n N_n + \mathrm{NLR}_n + D_n - T^c_n, \tag{12}$$

where net land revenue deducts activation costs and, under Entropy Logit, management costs. Goods markets, labor markets, and international payments clear. Prices, wages, land returns, quantities, and sourcing shares are jointly determined.

We solve the counterfactual in exact changes, $\widehat{x} = x'/x$ (Dekle et al., 2008). The final-consumption subsidy adjusts to satisfy

$$\widehat{Q}_{\mathrm{USA,bio}} = 56.7/6.55 = 8.65649. \tag{13}$$

Land returns and other equilibrium outcomes adjust jointly with the subsidy. As a robustness exercise, we subsidize producers while keeping the same U.S. biofuel-output target.

3. Allocation, Productivity, and Counterfactual Responses

We compare how returns affect land allocation and how allocated land contributes to production. We first hold return changes fixed and then consider their equilibrium feedback through prices and quantities. The results apply to either land-allocation nest while holding the other fixed. Online Appendices B and C illustrate the complete propositions and proofs.

3.1. Physical shares and transformed services

Let s_i^0 and v_i^0 denote benchmark physical-area and land-revenue shares. Under Fréchet or ACET, the exact proportional response of a physical share is

$$\widehat{s}_i = \frac{\widehat{r}_i^{\nu}}{\sum_j s_j^0 \widehat{r}_j^{\nu}}. \tag{14}$$

Fixed preference or allocation shifters are absorbed in the benchmark shares. The two specifications therefore have the same conditional share response when s^0, ν, and the return changes coincide. Under Fréchet, however, the return governing land allocation is based on productivity before selection, while observed payments per hectare reflect the productivity of the plots selected into each use.

Under CET, the corresponding response is

$$\widehat{b}_i = \frac{\widehat{r}_i^{\eta}}{\left(\sum_j v_j^0 \widehat{r}_j^{1+\eta}\right)^{\eta/(1+\eta)}}. \tag{15}$$

The aggregate uses revenue shares and a different exponent, even when $\eta = \nu$. The physical-land specifications impose $\sum_i \Delta L_i = 0$ within each land-source cell, while CET constrains a composite of productive land services. We express CET quantities in benchmark-hectare units for comparison, but they do not represent physical hectares.

3.2. Return metrics and local responses

For a pair of uses with $\Delta r_i = r_i' - r_i$, the change in relative allocations satisfies

$$\log \frac{\widehat{s}_i}{\widehat{s}_j} = \begin{cases} \nu \log(\widehat{r}_i/\widehat{r}_j), & \text{Fréchet and ACET,} \\ \alpha(\Delta r_i - \Delta r_j), & \text{Classical Logit,} \\ \alpha\{\Delta(r_i/W^m) - \Delta(r_j/W^m)\}, & \text{Entropy Logit.} \end{cases} \tag{16}$$

CET has the first expression with s replaced by b and ν by η. A proportional-return coefficient is dimensionless. A Logit scale converts return levels, or returns relative to management costs, into share changes. A comparison therefore requires translating the parameters into a common return-response measure.

The local responses in Table 1 depend on revenue shares under CET, physical shares under Fréchet and ACET, and both physical shares and return levels under Logit. As

Table 1. Local responses to proportional return changes

Specification	Own-return elasticity	Cross-return elasticity, $j \neq i$
Fréchet / ACET	$\nu(1 - s_i)$	$-\nu s_j$
CET	$\eta(1 - v_i)$	$-\eta v_j$
Classical Logit	$\alpha r_i(1 - s_i)$	$-\alpha r_j s_j$
Entropy Logit	$\alpha(r_i / W^m)(1 - s_i)$	$-\alpha(r_j / W^m) s_j$

Elasticities refer to physical shares except under CET, where they refer to productive land services. The Entropy Logit derivatives hold the management-service price fixed. All derivatives hold other returns fixed.

equilibrium returns change, the Logit response changes even when α remains fixed.

The choice of return measure matters when initial returns vary across uses.A return rising from 50 to 60 increases by 20 percent but by 10 in levels, while a return rising from 500 to 550 increases by 10 percent but by 50 in levels. The proportional-return and Logit specifications therefore rank these two changes differently. Equilibrium acreage also depends on initial shares, other returns, and the nesting structure.

3.3. Productivity selection and output

The Fréchet selection mechanism implies

$$\mathbb{E}[e_i(q) \mid q \in \Omega_i] = E_i s_i^{-1/\nu}. \tag{17}$$

Holding other production inputs and total land fixed, output is therefore proportional to

$$Q_i = K_i \bar{L} E_i s_i^{(\nu-1)/\nu}, \qquad K_i = (\gamma_i^L)^{-1} \hbar_i. \tag{18}$$

ACET and the two Logit specifications have s_i in place of $s_i^{(\nu-1)/\nu}$, while CET has the land-service quantity b_i. Under Fréchet, productive land increases less than physical acreage because expansion brings less productive plots into the use. The same acreage response can therefore produce different output responses across specifications.

Let $\mathcal{L}_i = \bar{L} s_i$ denote acreage. Holding K_i fixed, the ratio of marginal to average productivity is

$$\frac{\partial Q_i / \partial \mathcal{L}_i}{Q_i / \mathcal{L}_i} = \frac{\nu - 1}{\nu}. \tag{19}$$

For a finite expansion by a factor $a > 1$, incremental output per added hectare relative to initial output per hectare is

$$\frac{(Q_i' - Q_i)/(\mathcal{L}_i' - \mathcal{L}_i)}{Q_i / \mathcal{L}_i} = \frac{a^{(\nu-1)/\nu} - 1}{a - 1}. \tag{20}$$

These expressions isolate productivity selection by holding input intensity and the other allocation margin fixed. Observed yield changes also reflect changes in these factors.

3.4. *Land-response and output-response calibration*

Fréchet and CET can be calibrated to produce the same response of productive land. Combining (14) and (18) gives

$$\widehat{H}_i^F = \frac{\widehat{r}_i^{\nu-1}}{\left(\sum_j s_j^0 \widehat{r}_j^{\nu}\right)^{(\nu-1)/\nu}}, \tag{21}$$

where H_i denotes productive land, holding the other production terms fixed. Equation (15) gives the same response when $\eta = \nu - 1$, $v^0 = s^0$, and the return changes are defined consistently. Gouel et al. (2026) establish this production equivalence, while physical acreage responses remain different.

In the baseline, we use the same proportional-return coefficients in the allocation equations and take physical and revenue weights from the same benchmark data. This does not equalize local output-supply responses. Section 6.2 compares Fréchet at $(2.10, 2.38)$ with baseline ACET at $(1.10, 1.38)$, aligning the productive-land response coefficients $\nu_m^F - 1 = \nu_m^A$ at both nests. The return aggregates and equilibrium feedbacks remain specification-specific.

In general equilibrium, productivity selection affects production costs and factor demand, which in turn affect commodity prices, trade, land returns, and allocation. The Classical–Entropy Logit comparison also reflects differences in resource use and the scaling of returns by management costs. Our comparisons include these mechanisms and their equilibrium feedbacks.

4. Data and Calibration

4.1. *The common benchmark*

We use the 2001 GTAP-BIO benchmark underlying the maize-ethanol experiment in Hertel et al. (2010). The aggregation has 18 regions, ten production sectors, eight land uses, and 18 AEZ land types. GTAP-BIO provides bilateral expenditure, production, intermediate inputs, final demand, factor payments, energy substitution parameters, land cover, and harvested area (Dimaranan, 2006; Birur et al., 2008). Labor endowments are based on persons engaged from the Penn World Table (Feenstra et al., 2015). Online Appendix D documents the accounts and concordances.

The sector aggregation assigns distillers' dried grains with solubles (DDGS) and biodiesel by-products to OtherGoods. Their benchmark transactions are included in that sector, whose non-energy intermediate demands are Cobb–Douglas. The counterfactual does not explicitly link additional biofuel production to feed by-products or allow those by-products to substitute for grain. Section 5.3 discusses this treatment when comparing emissions levels.

We construct sourcing shares from bilateral purchases and destination expenditure, and production shares from factor and intermediate payments. We form the energy bundles before calculating final and intermediate expenditure shares. Harvested-area data allocate cropland across crops, while the broad land-cover categories provide pasture, managed forest, and idle land, with unmanaged mapped to the idle category. We use the same benchmark quantities and shares in every specification and recover model-specific shifters and the unobserved idle return from the benchmark conditions.

To identify the unobserved idle return, we set land-activation labor payments to 5 percent of total production and activation labor payments:

$$\frac{T_n^{\text{setup}}}{\sum_j \gamma_{n,j}^N Y_{n,j} + T_n^{\text{setup}}} = 0.05. \tag{22}$$

We impose this restriction at the country level and account for Entropy Logit's management labor separately. The restriction identifies the idle return. Estimating conversion costs per hectare would require separate evidence.

4.2. *Land response*

In our standard calibration, we set the Fréchet and ACET proportional-return coefficients to 1.10 across broad land uses and 1.38 within cropland (Table 2). The lower-nest value follows Farrokhi and Pellegrina (2023), while we choose the upper-nest value to satisfy the nested Fréchet restrictions. CET uses the same coefficients. Table 1 shows the remaining differences in own- and cross-return responses at these values.

We choose the Logit scales to approximate the corresponding local responses using benchmark shares and returns. Because one scale applies to uses with different returns, it cannot generally match all responses exactly. Online Appendix E gives the criterion and model-specific inversions.

At the Fréchet parameters $\nu_1 = 1.10$ and $\nu_2 = 1.38$, equation (19) gives conditional marginal-to-average productivity ratios of 0.091 and 0.275. Parameters close to the finite-mean boundary therefore imply strong productivity selection and relatively small allocation responses.

Lark et al. (2020) estimate representative yields on U.S. cropland converted between 2008 and 2016 and report an average shortfall of 6.5 percent relative to the national average on existing cropland. Their national comparison reflects where conversion occurs,

Table 2. Baseline land-response calibration

Specification	Broad land	Crops	Restriction
Fréchet	1.10	1.38	Proportional-return coefficients in the two allocation nests.
ACET	1.10	1.38	The same proportional-return coefficients, with physical area adding up.
CET	1.10	1.38	The same coefficients, with return aggregates based on revenue weights.
Classical Logit	Locally calibrated scales		Approximation to the benchmark proportional responses.
Entropy Logit	Locally calibrated scales		The same local responses, with returns scaled by management costs.

The coefficients govern relative allocation responses. Local land and output-supply elasticities also depend on aggregation weights and productivity selection. Online Appendix E gives the weighting and inversion formulas.

while their crop-specific local differences are much smaller. These estimates measure a related empirical margin, but not the conditional derivative in (19). They combine geographic and crop variation with differences in local biophysical conditions. Setting $(\nu - 1)/\nu = 0.935$ would mechanically imply $\nu \simeq 15.4$, but this is not an estimate of our parameter. Disciplining productivity selection requires evidence that matches the land source, crop, comparison group, and treatment of inputs.

4.3. *Trade, energy, and the experiment*

We use the sector-specific GTAP-BIO sourcing elasticities reported in Online Appendix I. Section 6 considers alternative trade calibrations. Biofuel and other energy are imperfect substitutes in intermediate and final demand. The country-specific energy parameters are 3.20 for the United States, 1.50 for EU27, 1.10 for Brazil, and 2.00 for the remaining regions. We suppress country subscripts in the model exposition.

Following Hertel et al. (2010), we raise U.S. biofuel output to 8.656 times its benchmark level in (13). The resulting 56.7 billion liters correspond approximately to the 15-billion-gallon conventional-fuel quantity implied by the original statutory schedule (United States Congress, 2007). We use this expansion as a common demand experiment, not as an estimate of the policy's contribution to production growth.

4.4. *Environmental accounting*

We apply the same carbon factors by land type and source to all physical-land counterfactuals. Let $e^{-}_{n,k,\tau}$ and $e^{+}_{n,k,\tau}$ denote the carbon released from a net loss of one hectare and stored from a net gain. The resulting stock loss is

$$E^L = \sum_{n,k,\tau} \left\{ e^-_{n,k,\tau}[-\Delta L_{n,k,\tau}]_+ - e^+_{n,k,\tau}[\Delta L_{n,k,\tau}]_+ \right\}, \tag{23}$$

where $[x]_+ = \max(x, 0)$. The physical-land specifications preserve total area within each country–AEZ cell. All five crops receive the same cropland factor. We assign zero direct carbon to idle land, while managed-forest losses and gains can have different factors. Because the calculation uses net area changes, it does not capture simultaneous gross clearing and regrowth within a cell. Assigning zero direct carbon to idle land is an accounting assumption and does not imply that idle land contains no carbon. Section 6.3 reports calculations with positive idle-land carbon factors.

For CET, we apply the same carbon factors directly to its productive land-service quantities. Because these quantities are not physical hectares, the resulting carbon calculation is a diagnostic rather than a physical land-conversion estimate. We therefore report it separately from the four physical-land estimates. Online Appendix G gives the accounting identities and discusses the limits of interpreting net changes as land transitions.

We then calculate the annual change in production-based fossil-fuel CO_2 using benchmark country–sector emissions intensities and counterfactual production. We report this flow separately from the one-time land-carbon stock loss.

5. Quantitative Results: Land, Commodity Markets, and Carbon

5.1. Output and acreage

We find similar increases in U.S. coarse-grains output across the five specifications, ranging from 30.7 to 33.4 percent (Figure 1). Physical acreage increases range from about 9.5 percent under Logit to 32.2 percent under Fréchet. ACET produces a 33.2 percent output increase with a 17.8 percent acreage increase. CET's 19.0 percent response measures productive land services rather than physical hectares.

These output and acreage responses imply a 1.2 percent decline in output per hectare under Fréchet and a 13.0 percent increase under ACET. Under Fréchet, expansion brings less productive plots into use, while aggregate yield changes also reflect input intensification and changes in the composition of land sources.

Global coarse-grains area expands by 17.94 million hectares under Fréchet, 9.68 under ACET, and about 5.2 under either Logit specification (Figure 2). The other four crops contract by 3.69 million hectares under Fréchet and 2.22 under ACET, but expand by about 1.3 million hectares under Logit. Sugarcane expands globally under all four physical-land specifications.

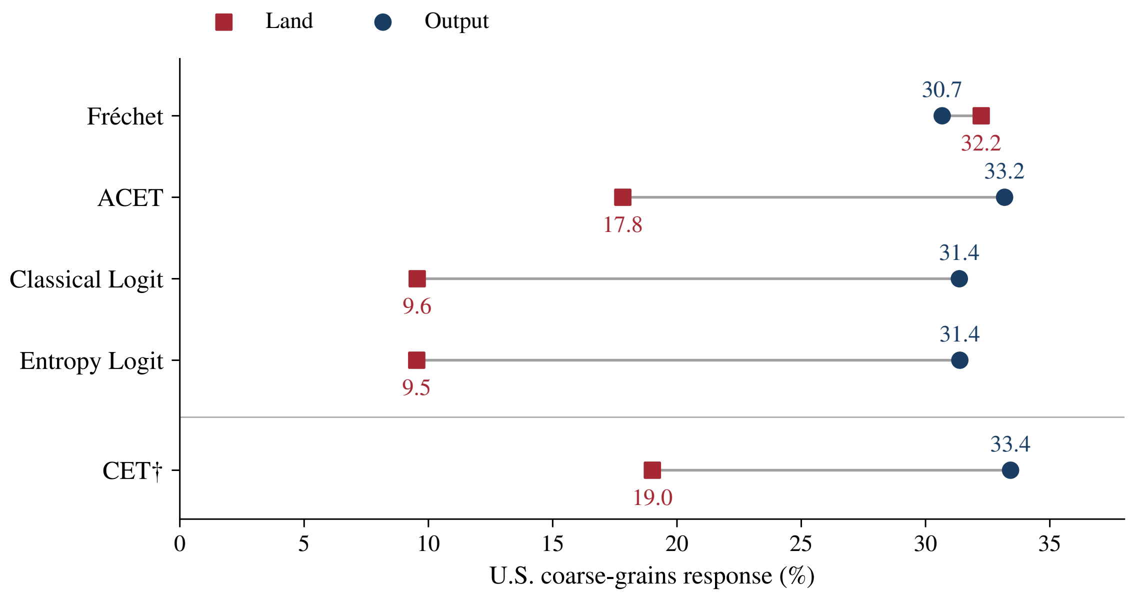

Figure 1. U.S. coarse-grains output and land responses

Notes: The final-consumption subsidy implements the same U.S. biofuel output in each specification. Labels report percentage changes. †CET land is a transformed service quantity.

The source of new cropland also differs across specifications. Total cropland expands by approximately 14.3 million hectares under Fréchet, 7.5 under ACET, and 6.5 under the Logit specifications. Managed-forest losses are 6.93, 3.14, and about 3.6 million hectares, respectively. ACET therefore converts less managed forest than Logit despite its larger cropland expansion, with more of its new cropland coming from idle land.

5.2. International and cross-crop adjustment

Coarse-grains prices generally rise across regions, with some small changes rounding to zero. In the United States, the increase ranges from 2.30 percent under CET to 4.09 percent under Fréchet. U.S. coarse-grains imports rise and exports fall under every specification. Foreign acreage also expands, but most additional coarse-grains land remains in the United States. Table 3 separates the domestic and foreign responses. Foreign land accounts for about 11–13 percent of global coarse-grains expansion among the physical-land specifications.

U.S. producer prices for oilseeds, sugarcane, other grains, and other agriculture rise under the proportional-return specifications and fall under the two Logit specifications (Figure 3). This contrast reflects differences in how land shifts across crops. Competing crops expand in aggregate under Logit and contract under the proportional-return specifications as prices and land allocation adjust jointly.

These joint price and acreage responses can be compared with evidence from an identi-

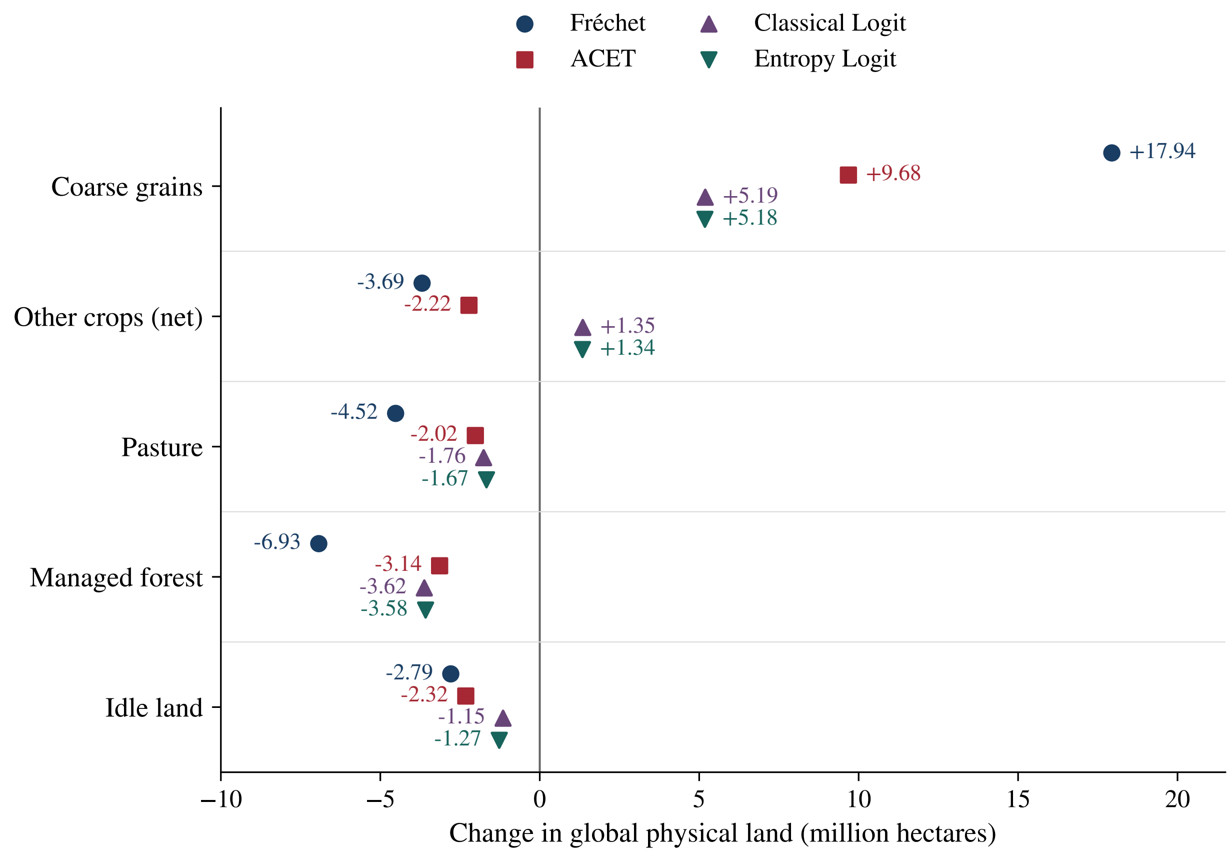

Figure 2. The amount and composition of physical land adjustment

Notes: Final-consumption-subsidy responses. Other crops aggregate Oilseeds, Sugarcane, Other grains, and Other agriculture. The figure reports net changes in each land category. CET service quantities are reported separately in Online Appendix H.

Table 3. Domestic and foreign physical land adjustment

	Coarse-grains expansion		Managed-forest loss	
Specification	United States	Foreign	United States	Foreign
Fréchet	15.65	2.29	5.84	1.09
ACET	8.65	1.03	2.70	0.44
Classical Logit	4.64	0.55	3.24	0.38
Entropy Logit	4.63	0.55	3.23	0.35

Notes: All entries are million hectares under the final-consumption subsidy. Foreign changes equal global changes less U.S. changes, using rounded entries. Positive forest entries denote losses. The table records the location of adjustment in the open-economy counterfactual.

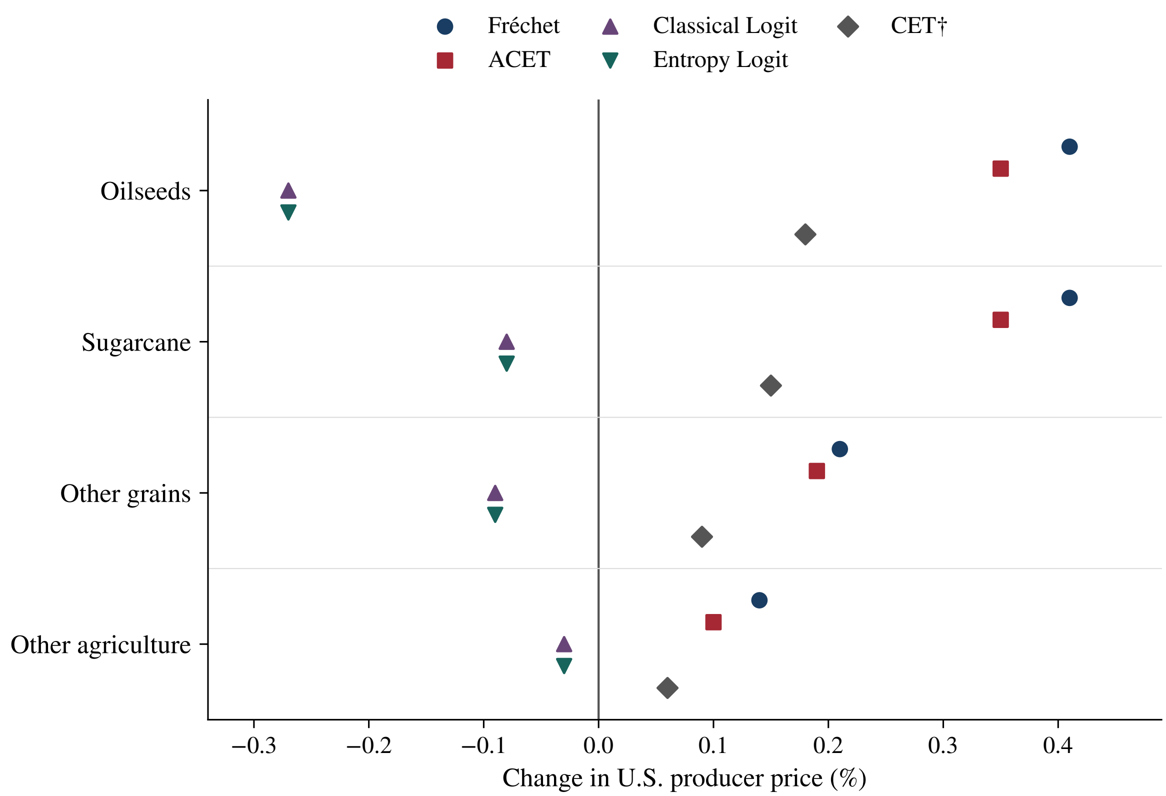

Figure 3. Competing-crop producer prices in the United States

Notes: Percentage changes under the final-consumption subsidy. The coarse-grains price rises in all five specifications. Small vertical offsets separate the model predictions within each crop.

Table 4. Carbon effects of the final-consumption subsidy

Specification	Land-use carbon ($MtCO_2e$)	30-year intensity (gCO_2e/MJ)	Annual CO_2 (Mt/year)
Fréchet	5,287	165.8	-70.7
ACET	2,423	76.0	-59.2
Classical Logit	2,743	86.0	-58.2
Entropy Logit	2,719	85.3	-56.8
CET†	1,167	36.6	-68.2

Notes: Land-use carbon is a one-time stock loss. Annual CO_2 is the change in production-based fossil-fuel emissions. The intensity divides the stock loss by 30 years of the additional 50.15 billion liters, at an assumed 21.2 MJ per liter. This conversion is not a lifecycle estimate. †CET applies the same carbon factors to transformed branch quantities; it is a diagnostic proxy, not a physically balanced conversion estimate.

fied feedstock-demand shock, after accounting for common weather, input-cost, and other demand changes. Online Appendix H reports the country-level coarse-grains responses, and the accompanying data include all reported sectors.

5.3. *Carbon consequences*

Among the physical-land specifications, one-time land-use carbon losses range from 2,423 $MtCO_2e$ under ACET to 5,287 $MtCO_2e$ under Fréchet (Table 4). Classical and Entropy Logit lie between these values. Logit converts less land to cropland than ACET but more managed forest, resulting in larger carbon losses under the same carbon factors.

We express the stock changes per unit of incremental fuel output using 21.2 MJ per liter and a 30-year accounting horizon:

$$I_{30} = \frac{10^{12} E^{L}_{\mathrm{Mt}}}{30\,(56.7 - 6.55)\,10^{9}\,21.2} \quad \mathrm{gCO_2e/MJ}. \tag{24}$$

The physical-land estimates correspond to approximately 76–166 gCO_2e/MJ. This conversion spreads the one-time stock loss over 30 years of additional annual fuel production and is not a complete lifecycle carbon intensity.

These estimates are about three to six times the 27 gCO_2e/MJ reported by Hertel et al. (2010). U.S. coarse-grains output rises by about 31–33 percent in our model, compared with 17 percent in their analysis (Online Appendix H). This difference may partly reflect our treatment of by-products. DDGS enters OtherGoods, and additional biofuel production does not explicitly increase feed by-products that substitute for grain. Hertel et al. (2010) report that market-mediated responses and by-product use jointly reduce cropland conversion by 72 percent relative to the land used for ethanol feedstocks. Quantifying how much this mechanism explains the difference in emissions would require a directly comparable counterfactual. All five land specifications share our treatment of by-products, holding it fixed so that differences across them reflect the land specification.

The source of new cropland also matters for the level of carbon losses. The physical-land specifications reduce U.S. managed forest by 2.7–5.8 million hectares (Table 3). In contrast, Lark et al. (2020) find that grasslands, including pasture and hay, account for 88 percent of U.S. land converted to crop production in 2008–2016. Their study measures gross conversion in a later period with different land classifications, while our counterfactual measures net changes from a 2001 benchmark.

CET produces a carbon calculation of 1,167 $MtCO_2e$ when the carbon factors are applied directly to its productive land-service quantities. Cropland services increase by 9.47 million benchmark units, while pasture, forest, and idle-land services decline by only 3.21 million units. About two-thirds of the increase in cropland services therefore does not correspond to land leaving these other uses. Because CET does not preserve physical area, converting this result into a physical carbon estimate requires a separate mapping from land services to hectares. We therefore report the CET calculation separately from the four physical-land estimates.

Annual production-based fossil-fuel emissions fall by about 57–71 $MtCO_2$ per year across specifications. We report these flows separately from the one-time land-carbon stock losses. Calculating carbon payback would also require the timing of land-carbon release, the duration of production changes, and consistent lifecycle coverage.

6. Sensitivity to the Experiment and Calibration

6.1. The size of the biofuel expansion

We raise U.S. biofuel output to two, four, six, and 8.656 times its benchmark level. Fréchet's land-use carbon loss increases from approximately 690 to 5,287 $MtCO_2e$, while ACET's increases from 330 to 2,423 $MtCO_2e$ (Figure 4). The gap is already substantial when biofuel output doubles. Larger expansions widen the absolute gap, with the ratio staying close to two. Online Appendix I reports the corresponding coarse-grains land responses.

6.2. Land responsiveness and productivity

We raise Fréchet's coefficients from $(1.10, 1.38)$ to $(1.50, 1.66)$ and $(2.10, 2.38)$. The conditional marginal-to-average productivity ratio at the broad-land margin increases from 0.091 to 0.333 and 0.524, respectively. At the higher pair, $\nu_m^F - 1 = \nu_m^A$ matches the productive-land response coefficients of baseline ACET at both nests, without imposing equality of the full equilibrium responses.

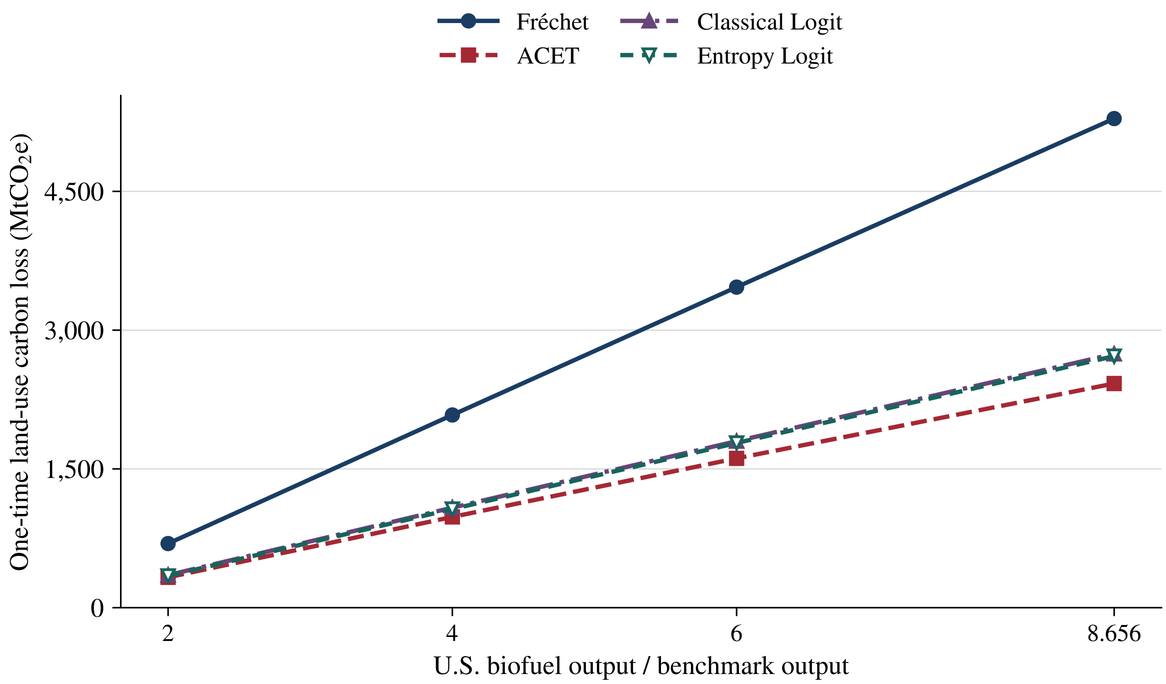

Figure 4. Land-use carbon under alternative biofuel expansions
Notes: All parameters and the final-consumption subsidy instrument are held fixed. Each marker is a separately solved counterfactual; lines connect reported points. Physical-land specifications only.

Table 5. Fréchet recalibration and baseline ACET

Specification	(ν_1, ν_2)	U.S. output (%)	U.S. acreage (%)	Global cropland (Mha)	Land carbon ($MtCO_2e$)
Fréchet	$(1.10, 1.38)$	30.67	32.24	14.25	5,287
Fréchet	$(1.50, 1.66)$	31.74	32.75	14.66	5,174
Fréchet	$(2.10, 2.38)$	33.12	33.48	15.10	4,916
ACET	$(1.10, 1.38)$	33.18	17.82	7.47	2,423

Notes: Output and acreage refer to coarse grains. All rows use the baseline biofuel expansion and zero direct carbon on idle land. The Fréchet coefficients $(2.10, 2.38)$ satisfy $\nu_m^F - 1 = \nu_m^A$ relative to baseline ACET at both nests. This aligns the productive-land response coefficients, without imposing equality of the complete equilibrium responses.

We find that this comparison nearly closes the output gap but leaves the physical land and carbon gaps substantial (Table 5). U.S. coarse-grains output rises by 33.12 percent under Fréchet and 33.18 percent under baseline ACET, while acreage rises by 33.48 and 17.82 percent. Fréchet's carbon loss falls from 5,287 to 4,916 $MtCO_2e$, still 2.03 times ACET's 2,423 $MtCO_2e$. Higher coefficients weaken selection but also increase land responsiveness. Global cropland expansion rises from 14.25 to 15.10 million hectares, while managed-forest losses fall from 6.93 to 6.35 million hectares and idle-land losses rise from 2.79 to 4.62 million hectares.

The earlier ACET calculations provide a separate comparison at common allocation coefficients. When both specifications use $(2.10, 2.38)$, their carbon ratio is 1.67. Online Appendix I reports these results, the smaller upper-nest changes, and the lower-nest exercise. The latter holds the upper coefficient at 1.10 and raises the crop coefficient from 1.10 to 2.46: Fréchet's carbon loss falls, ACET changes little, and the Logit estimates rise.

6.3. *Trade, policy, and carbon accounting*

We compare GTAP-BIO trade elasticities with the sector-specific estimates of Fontagné et al. (2022) and common CES sourcing parameters of 3.12 and 5.14 based on Boehm et al. (2023) and Simonovska and Waugh (2014). Fréchet's carbon estimates range from approximately 5,130 to 5,330 $MtCO_2e$, while ACET's range from 2,370 to 2,450 $MtCO_2e$. Online Appendix I reports the parameter conversions and results. These within-specification changes are small relative to the baseline Fréchet–ACET gap.

A production subsidy implementing the same U.S. biofuel output preserves the baseline ordering of physical-land carbon losses, from approximately 2,340 $MtCO_2e$ under ACET to 5,130 $MtCO_2e$ under Fréchet. Annual production-based emissions reductions are smaller, at about 8–21 $MtCO_2$ per year. Online Appendix H reports the full results.

With physical allocations fixed, replacing the zero idle-land factor with pasture factors raises Fréchet's carbon loss to 5,575 $MtCO_2e$ and ACET's to 2,666 $MtCO_2e$. A 50–50 mixture of pasture and forest factors gives 6,373 under Fréchet, 3,351 under ACET, 3,249 under Classical Logit, and 3,242 under Entropy Logit (Online Appendix I). ACET then exceeds both Logit estimates because it converts more idle land. These accounting cases use the baseline coefficients; they are separate from the Fréchet recalibrations above.

7. Conclusion

We find that the choice of land specification changes land-use carbon losses by more than a factor of two, even though feedstock output responds similarly across specifications. When U.S. biofuel production rises to 8.7 times its benchmark level, carbon losses range from 2,423 to 5,287 $MtCO_2e$ across the four specifications that allocate physical hectares.

With Fréchet's productive-land response coefficients aligned with baseline ACET's, output responses are almost identical, but the carbon ratio remains 2.03.

We use a unified general-equilibrium framework to show how three features of these specifications account for the differences. Under Fréchet, expansion brings less productive land into crops, increasing the acreage required for a given output response. CET allocates productive land rather than physical hectares and therefore requires a separate mapping to hectares for carbon accounting. Logit responds to return levels rather than percentage changes, affecting how land shifts across crops.

These mechanisms generate different predictions for acreage, the productivity of land entering cultivation, and the sources of new cropland. Evidence on these outcomes can therefore help distinguish among land specifications. The level of the carbon estimates also depends on other features, including feed by-product substitution and the shares of forest and grassland converted. The dependence of carbon consequences on land allocation thus cautions against basing regulation on a single model specification.

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