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Evaluating the Economic Basis for GTAP and Its Use for Modeling Biofuel Land Use

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Increased biofuel use requires crops, producing crops requires cropland, and producing cropland causes losses of carbon from vegetation and soils. In a typical lifecycle context for products other than biofuels, carbon accounting attributes to each product the emissions from each input, including some of the emissions of fixed inputs to each output if they are significant. For example, some of the emissions of producing a car factory are assigned to each car. Following this straightforward approach, some of the carbon emissions of producing cropland should be assigned to each gallon of biofuel. This standard lifecycle approach makes the emissions from biofuels high because, as discussed below, the average emissions to generate a hectare of cropland greatly exceed the reduced emissions from gasoline or diesel that result from 30 years of biofuel production on that hectare.

In determining the emissions from the use of cropland for biofuels, however, governments have sometimes relied instead on complex, global economic models to estimate how much carbon will be lost from land conversion that occurs to replace crops diverted from food to biofuels, known as indirect land use change, or “ILUC”. These models can claim fewer emissions than the past average carbon losses for a crop for a variety of reasons: claims that some or much food is not replaced, claims that higher food prices lead farmers to produce more food on the same land, or for some reason, claims that the land converted to generate each additional ton of crop loses less carbon than the global average. In general, these models claim to show how biofuel demand will reallocate land in each part of the world through not just global but national or regional market pricing mechanisms, sometimes claiming to factor in interactions with the entire global economy.

GTAP is one model used to estimate ILUC, with one version used by the California Air Resources Board (CARB) and changed versions used as inputs to the GREET model at the U.S. Department of Energy. In both versions, estimated ILUC carbon losses from a gallon of corn ethanol and soybean biodiesel are extremely low, meaning there is little carbon cost for

[1] The research on which this report continues. Comments welcome to steven.berry@yale.edu and some further improvements are likely. Berry: Yale University Department of Economics and Tobin Center. Searchinger: Princeton University and Tobin Center. Yang: Yale University and Tobin Center. We thank Thomas Hertel, Farzad Taheripour, Marinos Tsigas, Xin Zhao, and Alla Golub for their helpful responses to inquiries. The results and opinions here are solely the responsibility of the authors.

diverting even vast areas of prime farmland to biofuel production. To serve this function, the GTAP model must be scientifically credible. This report evaluates GTAP's economics. It finds that GTAP lacks a credible economic foundation. GTAP is particularly unable to credibly evaluate land use changes.

- Of thousands of economic parameters, only a small number claim to have any direct, empirical basis. Of these, few of the cited empirical studies make any use of credible techniques for distinguishing correlation from causation and, most fundamentally, supply from demand. Regardless, these parameters are all or nearly all misapplied to data, regions, and functional forms that differ fundamentally from the original empirical results and therefore lose any statistical validity. GTAP is doing the equivalent of using parameters estimated of how the effectiveness of a drug varies by weight to estimate how its effectiveness varies by height. In effect, these parameters are claimed to predict changes in supply and demand that they do not.

- GTAP's basic economic structure is particularly unsuited to the analysis of land use change because its economic components do not reallocate land among different uses, such as pasture or forest to cropland, but instead destroy or create large quantities of physical land. These physically impossible changes in land area are then arbitrarily adjusted back to respect the actual finite quantity of land. Such "hand of God" adjustments are inherently invalid. In GTAP, these adjustments also radically reduce the ILUC results and even shrink the share of land use change from GTAP's version of forests.

- We also find that the purely assumed functional form of the GTAP model, to which parameters are misapplied, inherently leads to limited conversion of forests and low ILUC. As one example, the functional form leads GTAP to select incorrect parameters from the one underlying study that GTAP uses to estimate the "elasticity" of conversion of cropland to forest and forest to cropland. This deliberately overestimated elasticity has the effect of overestimating the economic resistance of forests to conversion by cropland, leading to limited conversion of forests. Related features also cause forests to instantly reappear in new areas. In some cases, the structural form leads to bizarre results.

- The model's structural form also cannot allow conversion of unmanaged land, which is much of the world's carbon-rich land. It also contains no notion of a standing forest that can exist for multiple reasons – there is only land that exists to produce wood. These assumptions not only force the model to ignore a major direct source of potential land use change, unmanaged land, but work backward to limit the model's loss of managed forests and even of grasslands.

- GTAP uses an outdated trade model that is designed to capture patterns of trade in manufactured goods. Applying this model to agricultural products artificially limits the predicted effects of US policy on world land use.

- We also review how additional, empirically unsupported decisions added to the model since the first version used for CARB have further reduced the estimated ILUC. As an example, the model makes a pure assumption, without any supporting economic analysis, that most new cropping area will be supplied not by expansion of cropland but by cropping existing cropland more frequently. This assumption also contradicts actual experience in the U.S.

Benchmarking ILUC

Global cropland for annual crops is expanding at an increasing rate: according to a recent, high-quality satellite-based study, annual cropland is increasing at a net rate of 10 million hectares per year (and a gross rate of roughly twice that) (Potapov et al. 2021), roughly equal to the annual harvested cropland area of Iowa. Although data limitations impede analysis of net changes in pasture area, satellites show that expansion of pasture is an even larger direct source of deforestation than cropland (Weisse and Goldman 2021).

To determine a useful benchmark for ILUC, we can ask on average how much carbon has been lost from vegetation and soils to produce the crops that go into one gallon (or one mega joule) of each biofuel. Following both national and California policy, we can then amortize, i.e., divide, this carbon loss over 30 years of biofuel production. This calculation generates an ILUC if the crop, such as corn diverted to biofuels, is replaced by the same quantity of corn on new cropland with the average global yield and with the average carbon losses that have occurred from previous cropland expansion for corn. This is the same approach taken generally for all inputs in lifecycle analyses, including for other inputs used for corn.

As shown in Table 1 (and estimated in Searchinger et al. 2018), this theoretical ILUC is 200 gCO_2/MJ for corn ethanol and 330 gCO_2/MJ of biodiesel. That number, which excludes the production emissions from use of fertilizer and fossil fuels, is roughly 3-4.5 times the direct fossil fuel savings from the use of the biofuel. By this benchmark, the GTAP ILUC estimate used by CARB is only around 10% of these average emissions in generating cropland to produce corn and soybeans. That estimated ILUC is also only around 25% of the carbon that could be sequestered by allowing U.S. corn land to grow forest (assuming carbon sequestration at 3tC/ha/year). (See Table 1). The GTAP versions incorporated into the GREET model are even lower. Implicitly, they are claiming that all the cropland in Iowa can be diverted to biofuel production -- or to any other use -- with almost no effect on global land use elsewhere and almost no resulting climate consequences.

The GTAP estimates are also far below estimates of some other recent economic model estimates. In (Lark et al. 2022), the authors found that ILUC emissions in the U.S. alone were 39 grams CO_2/MJ without counting international ILUC emissions. These high domestic emissions alone are particularly significant because international responses are likely to be higher. In Merfort et al. (2023), the authors estimated an ILUC of 92 grams CO_2/MJ for ethanol from high-yielding energy crops.

Table 1: Comparison of GTAP ILUC Estimates with Biophysical Carbon Costs

	Average global carbon loss to produce crop	Land use cost of not reforesting land at 3tC/hectare at U.S. yields	GTAP California ILUC estimate	GTAP-BIO ILUC estimate used by GREET	Exhaust pipe emissions from gasoline or diesel
Grams CO_2/mega joule					
Corn ethanol	200	83	22	7.8 – 14.3	
Soybean biodiesel	330	179	27	9.1-12.1	74

Biofuel figures are "land use cost" figures measured by the different methods excluding production emissions and excluding the portion of land attributable to co-products. Sources: Column 1 (Searchinger et al. 2018), column 2, author's calculations, column 3, CARB emissions estimates, column 4, GTAP results incorporated into GREET model outputs.

There are sound reasons to believe economic responses will not cause ILUC to be substantially less than those associated with the average loss of carbon in the past to create the requisite quantity of cropland. Rigorous econometric studies have shown that shocks to agricultural supply translate into similar price changes for crops around the world (Roberts and Schlenker 2013). This relationship means that increases in demand for biofuels in one region will cause similar price increases in different parts of the world and thereby stimulate cropland expansion wherever it is cheapest to do so. Although robust econometric studies are limited, where they are available, they have found that cropland expansion is highly sensitive to crop prices in carbon-rich parts of the world, such as Brazil in general and the Amazon in particular, particularly over a few years (Souza-Rodrigues 2019) (Sant'Anna 2024). These same rigorous studies have found that increased crop yields in response to higher prices play a much smaller role in replacing crops than agricultural expansion. Overall, these econometrically rigorous studies support the conclusion that cropland expansion in the parts of the world where cropland is expanding is the dominant way the market replaces crops diverted to biofuels.

The global, land use models that project substantially lower ILUC emissions than the benchmark do so for one or a combination of three reasons, all of which particularly contribute to GTAP's low ILUC estimates.

- First, a model may estimate that much of the food diverted to biofuels is not replaced because higher food prices depress consumption. New cropland is not therefore needed to replace much of the food. In the original GTAP estimates of ILUC from corn ethanol for CARB, roughly half of the food calories are not replaced. (Hertel et al. 2010)(T.D. Searchinger et al. 2015).

- Second, a model may claim that higher prices induce farmers to increase output per acre on existing agricultural land: This can occur by increasing crop yields, by intensifying pasture, or by increasing double-cropping or other forms of "cropping intensity. These effects also play a major role in GTAP (Malins, Plevin, and Edwards 2020) (Hertel et al. 2010) (Searchinger et al. 2015). In recent modeling, for example, the model predicts that 80% or more of additional cropping area in most regions is supplied not by new cropland but by growing crops on existing cropland more frequently (Malins, Plevin, and Edwards 2020).

- Third, the model may claim that converting land for new cropland releases little carbon. In recent GTAP runs for corn ethanol, 89% of the new cropland comes from grassland, with only 11% from forests (Table 1) (Taheripour, Zhao, and Tyner 2017) (Table 1). As discussed in Malins et al. (2020), some new versions of GTAP used for GREET also claim that converting much of this pasture to cropland gains soil carbon.

These functions may interact. In GTAP, for reasons discussed below, farmers directly convert overwhelmingly grassland rather than forest. In turn, livestock producers do not then significantly convert forests to replace grazing land either because GTAP projects reduced meat consumption or high livestock intensification.

The ILUC calculation depends in essence on the ratio of the three different responses to increased prices: agricultural land expansion, intensification, and food demand reductions. This means that <u>all</u> three responses must be soundly estimated to produce a scientifically useful ILUC estimate and errors in estimating any of these responses even in a single region could generate substantially flawed results.

Specific recent GTAP modifications that lead to a low ILUC

GTAP was originally used by the California Air Resources Board to establish an ILUC in 2010 but has undergone subsequent revisions. This section discusses specific parameter decisions made regarding GTAP, critiqued in Malins, Plevin, and Edwards (2020), and to which some GTAP modelers responded in Taheripour, Mueller, and Kwon (2021). These decisions by themselves will generate extremely low ILUC estimates in three ways:

- by increasing the "intensification" effect of cropland, so new cropland is not needed to replace crops;

- by increasing the intensification effect on pasture, so if pasture is converted to cropland, conversion of forest to pasture is not needed to replace the meat or milk;

- through adjustments to ensure that even more cropland expansion comes out of grassland not forest, plus assumptions that estimate conversion of much grassland to cropland causes little loss of carbon. Both changes reduce the carbon losses from expanding cropland.

Although the major contribution of this paper is to focus on the underlying model, we discuss first the issues raised by these recent changes because of their ability to greatly lower ILUC and because they help illustrate how a model can generate low ILUC estimates. We agree with the critiques in Malins et al., and we add some relevant additional observations.

1. Double cropping or other increases in cropping intensity

A major feature introduced into the model is an elasticity that ensures that at least 80% of the increase in cropping area in most regions, including the U.S., results not from expansion into native lands but from cropping the same cropland more frequently (Malins, Plevin, and Edwards 2020). Such a change is modeled as an increase in “cropping intensity.” This can occur, for example, by increasing the acres that produce two crops in a year, known as “double cropping.” Because doing so reduces the need for new cropland; an 80% increase in cropping intensity reduces ILUC by 80% (relative to the estimate without this effect).

As discussed in Malins et al., the GTAP authors have neither conducted nor cited any economic analysis that estimates that increased demand causes increases in double cropping or otherwise increases cropping intensity. What the authors appear to have done is simply adopt elasticities tailored by region, which they feel match recent cropland trends in these regions. Even if there were a trend toward increased cropping intensity, that does not mean that increased demand for crops drives this trend, let alone by how much if it contributes at all.

One way to highlight the flaw in this analysis is to compare the author’s claim that 80% of U.S. cropping will be provided by increases in cropping intensity with the contrary evidence of what has happened. Although there appeared to be a small increase in double-cropping in the U.S. in the first years of the renewable fuel standard mandate, there has since been a significant decline. Double cropping over the last five years was roughly 40% lower than between 2007-2011 and among the lowest levels ever recorded in USDA data. For overall cropping intensity, which also factors in how often land is left fallow or crops fail, there has been no discernible U.S. trend for decades. (USDA data available at https://www.ers.usda.gov/data-products/major-land-uses/major-land-uses/#Cropland). (For the remainder of the world, poor data makes it impossible to determine even what the true trends really are.[2]) If nothing else, this data calls the authors’ assumptions into question.

But this change also helps illustrate the improper economic data-analysis methods that are frequently used in designing the GTAP model. The “method” here is to treat short-run observed changes in double-cropping as reflecting a large, long-run causal effect of crop prices

[2] As Malins et al. correctly observe, the data from the FAO that estimates a country’s area of cropland and that estimates its area harvested come from different sources using different methods. The limitations in our understanding of cropping intensity are discussed in Searchinger et al. (2019), which provides examples of how FAO statistics can conflict with results from satellite studies.

on double-cropping. Having now seen the recent data on double cropping, if they followed their own method, the GTAP modelers would presumably adjust and remove this double cropping effect for the U.S. But of course, the original decision was not based on any serious attempt to distinguish causal relationships in the data. In fact, none of this data tells us about the real effect of prices on double cropping in either direction. We discuss these issues more broadly below.

More broadly, these kinds of ad hoc adjustments turn modeling into mathematical forms of storytelling. But any number of stories could be told from the same snippets of information. For double-cropping, alternative potential stories include that the original increase in double cropping was driven by non-price factors. Alternatively, increases in cropping intensity could be explained as a short-term response to increased demand before cropland area expanded to meet demand at a lower cost. The large number of potential and contradictory story lines are why economics requires rigorous methods to tease out the effects of changes in demand or supply.

2. Demand-induced yield gains of cropland and pasture

The GTAP modelers have similarly incorporated a substantial price-induced yield effect. This was originally based on a claimed set of U.S. papers for corn and then applied to every crop and to every country in the world. The lead author here reviewed these papers for the California Air Resources Board and determined that the papers relied upon actually as a whole found no yield intensification effect after the 1960's (Berry 2011). In fact, as discussed in Malins et al., corn yields in the U.S. follow an intensely linear trend independent of price. Furthermore, applying this intensification effect to other crops and to other regions lacks any foundation at all as the physical and economic factors that determine the ratio between land expansion and intensification will vary greatly by country.

In revisions to the model, as discussed in Malins et al., a large intensification effect has also been applied to pasture. As a result, when cropland expands into pasture, little pasture expands into forest to replace the meat or milk. As quoted in Malins et al. (2020), the GTAP authors conceded that this estimate does "'not have an empirical basis.'"

We add that this is a particularly significant, pure assumption. Expansion of pasture into forest is the main direct source of global deforestation (Weisse and Goldman 2021). Although lacking economic rigor, several papers have found statistical associations in Brazil between conversion of pasture to cropland and knock-on expansion of pasture into forest (Lapola et al. 2013)(Lapola et al. 2010) (Arima et al. 2011). A rigorous, econometric study has shown that increases in beef prices have a strong effect on deforestation in the Brazilian Amazon (Araujo, Costa, and Sant' Anna 2020), which implies a significant knock-on effect if pasture is converted to cropland elsewhere. Other unjustified model features, discussed below, lead GTAP to project that cropland will mainly expand into pasture. By assuming little need to replace the pasture, this pure assumption therefore has the effect of additionally assuming away much ILUC.

3. Cropland pasture

The introduction of a category of land called cropland pasture was one of the model features that leads the model to project even more conversion of pasture rather than forest. Cropland pasture is land that is occasionally cropped but is used for pasture, and it became the dominant GTAP-projected source of new cropland in both the U.S. and Brazil. This was not based on any kind of economic analysis but on an observation that as U.S. biofuel production rose, USDA was reporting a continuing decline in a land use category called cropland pasture. The primary effect of this change, given the GTAP structure, is to make it even more likely that cropland will expand into pasture rather than forest. (GTAP assumes that cropland will more likely switch from one cropland use to another than expand into new non-crop uses.) As Malins et al. observe, the GTAP-GREET versions of the model then further assume that this conversion increases soil carbon, contrary to virtually all other estimates of the effect of pasture conversion. This carbon assumption means that the cropland pasture assumption, as well as other elements of the model that lead cropland to expand into pasture rather than forest, cause even larger reductions in ILUC.

As discussed in both Malins et al. (2020) and Lark et al. (2022), this trend in cropland pasture is as likely based on definition changes and measurement inconsistencies as real changes, as USDA has cautioned. Malins et al. also observe that the GTAP authors employed no economic estimates to differentiate any changes in cropland pasture due to biofuels from trend line changes. And they observe that there is no international category of cropland pasture. [3] We agree with these critiques and add two observations.

First, the GTAP authors claim that the FAO category of "temporary pastures and meadows" is the global equivalent of cropland pasture, so they can apply it in Brazil (Taheripour, Mueller, and Kwon 2021). Even if this were true, in Brazil this category of land use has had a steady increase, not decrease, during the rise of biofuels, increasing in area by 20% from the average of 2003-05 average to the of 2019-2021. As in the case of double cropping, this is an example of how pure "story telling" goes awry, and why economic methods are needed instead to determine the effect of demand on land use changes.

[3] In Taheripour, Mueller, and Kwon (2021), the GTAP authors claim that the decline in cropland pasture was based on USDA data and large enough to accommodate increased land for biofuels even assuming losses to alternative uses. But this claim does not address the critiques. The GTAP authors did not perform an economic analysis to determine if increased demand leads to a decrease in cropland pastures. Moreover, if the data on cropland pasture is fundamentally flawed, it could not be used for economic analysis. There might be some trend in behavior, but not knowing the true quantity of cropland pasture, it would not be possible even to try to determine its causal factors. As stated in Lark et al. 2022: "[T]he source of cropland-pasture data in the United States is the 5-year interval Census of Agriculture, where the category is a subjectively interpreted aggregate variable that has undergone significant definition changes (Bigelow and Borchers (2017)) and measurement inconsistencies (USDA 2019; 2002) across time, further rendering it inappropriate for LUC assessment."

Second, the claim that converting cropland pasture to cropland increases soil carbon is not merely empirically unsupported but flawed conceptually because it is based on a failure to distinguish fluctuations in price from a structural shift in demand. This claim assumes that cropland pasture is marginal cropland that rotates in and out of cropping, which depresses its carbon stock relative to land used consistently as pasture (Taheripour, Mueller, and Kwon 2021). However, due to fluctuations in price, there will always be "frictional" cropland, i.e., land that is cropped in some years and not others. Even at a higher level of demand for crops due to the growth of ethanol, there will continue to be fluctuations in prices, so there will continue to be land cropped only in some years. There could be other structural economic changes that alter cropland pasture area, but there is no conceptual reason to believe, let alone econometrically established evidence, that the quantity of frictional cropland will decrease due to the rise of biofuels or other increases in demand.

GTAP'S Economic Foundation

This section goes beyond the specific, recent modeling choices discussed in *Malins et al.* to evaluate the GTAP model more generally. This part first explores the parameters and economic structure of the model. It finds that these lack an economic foundation. We then focus on the specific modeling of land use. We find that ILUC is reduced both by pure assumptions that dictate the structure of the model and particularly its land use components.

In both parts of this discussion, we show some results from running the 2010 version of GTAP-Bio. This is the only reasonably well-documented version of GTAP-Bio, and it is the version applied, with some adjustments, to generate the ILUC estimates for crop-based biofuels originally incorporated into regulations by CARB. Among our findings, we find that the basic structure of the model, by itself, can lead to odd and hard-to-explain results. One such flaw is that the economic equations in GTAP lead the model to destroy or create large quantities of land, which the model handles via a bolted-on adjustment factor that brings total land area back to its original level. In doing so, the model greatly reduces ILUC and the role played by deforestation.

This "hand of God" nonprice adjustment also contradicts the core rationale for using GTAP to study ILUC. The GTAP community often argues that some global equilibrium price model is necessary to evaluate ILUC. Both the climate benefits and costs of biofuels, including ILUC, are indeed driven entirely by the mechanisms of price changes. But GTAP's behavioral responses to price changes do not allocate actual., physical land. The resulting ad hoc nonprice adjustments contradict the entire rational for using GTAP in the first place. Whatever its other qualities, GTAP is therefore particularly inappropriate for estimating land effects.

1. **Basic Structure of Model**

At its essence, GTAP is a model for estimating shifts in supply and demand. For demand, it estimates how much changes in price for one good, whether corn, electricity, or various services, cause shifts in its consumption. (In economics, this is known as an "own-price" effect, often expressed as an "own-price elasticity."). GTAP also estimates how this change affects the consumption of other goods. For example, if the price of corn increases, and its consumption for food and feed declines, GTAP estimates what (and to what degree) other crops or foods replace those losses. (These are known as "cross-price" effects, often expressed as a "cross-price elasticity.") Price changes can affect consumption and production in a multitude of ways. For example, if corn prices increase, not only may livestock producers shift to other feeds, but the price of livestock products will increase, causing food consumers to shift to other foods and potentially to reduce their consumption of food overall, buying more of other goods. GTAP purports to predict all these effects.

The same adjustments occur on the supply side as producers of goods shift from one input to another. For example, if the demand for one form of energy increases, producers may not only shift to another form of energy but also reduce their energy consumption overall and shift a little to alternative inputs. GTAP purports to measure both the decline in consumption of each input whose prices increase and the shift to other inputs. GTAP purports to project these shifts, which are the core of the model, in a highly disaggregated ways: by country or groups of countries, by multiple agroecological zones (AEZs) within countries, and by product.

To do this, GTAP creates a hierarchical "tree" structure of layers, or "nests" of equations. Lower level nests result in aggregate products that are inputs to higher level nests. For example, a lower nest has the cropland used for different crop types, which compete with each other for use of cropland. The aggregate of these different uses of cropland generate a total cropland area, which is included in a higher level nest. At this higher level, cropland overall competes for the uses of total land with other uses of land, particularly grassland used for livestock and wood-producing land (GTAP's proxy for forests). Throughout the model, GTAP modelers group goods and inputs based on an intuition of which are likely to compete more directly with each other.

Within each nest, responses to price changes are based on two factors. First, there is a "substitution parameter", a single number, which is supposed to determine in general how likely it is that the quantity of goods produced, or the inputs used increase or decrease as a result of changes in price. We call this the "nest parameter."[4] However, this parameter by itself does not determine the sensitivity of change, i.e., the elasticity of supply or demand. Instead, as discussed more below, this elasticity depends both on that parameter and on a product's share

[4] In the literature, in ways that vary across the components of the model, this parameter might be called the "CES substitution parameter" or the "CET transformation parameter" or the "elasticity" parameter. The terms CES and CET refer to the restrictive functional forms of the model. The CES is somewhat modified in the consumer demand portions of the model, adding some additional flexibility, especially with respect to income.

of the total revenue of all products, or all inputs, within that nest.[5] For example, the elasticity of cropland area within each agroecological zone, i.e., the extent to which the area of cropland varies with a 1% change in price, depends on both the nest parameter and on the share of total rent cropland provides of all land uses in that agroecological zone. The revenue shares and the nest parameters are the only factors determining the substitution among products in the nest when the price of one product changes.

As a result, all supply and demand elasticities are determined by a single nest parameter for all products within a nest, and by the share of revenue or cost of each product within that nest.[6] This formula is chosen for its computational tractability not for its empirical reality. (As discussed below, it contradicts the limited economic analyses cited by the modelers to justify their choice of nest parameters.) This choice is understandable as a research strategy, but it does not produce a model that can be treated seriously as a policy tool.

2. **Absence of economically estimated parameters**

The first problem is that even if the overall formula were empirically grounded, its legitimacy still depends on thousands of necessary nest parameters. GTAP only even claims to base a handful of these parameters directly on *any* empirical economic analysis.

For the parameters that are claimed to have an empirical basis, none appear to be derived using modern econometrics. There is a very large literature on how to properly estimate demand and supply elasticities, including cross-price effects. It is the strong consensus of the economics profession that such estimates require changes in demand conditions ("instruments") to estimate supply, and vice-versa. For a famous application to biofuels, see Roberts and Schlenker (2013). For the consensus around this broad idea, see papers ranging from Wright (1928) to Berry and Haile (2021). To our knowledge, none of the thousands of parameters in GTAP is based on a high-quality application of consensus econometrics.

For others, although some reference may be made for an elasticity parameter, this parameter is nearly always based on analysis of a particular product in a particular location. GTAP's general approach is to apply the same parameters to quite different products or inputs and in multiple or all regions. In some cases, whole categories of parameters are set by pure assumption to a fixed fraction (such as one-half) of some other set of parameters.[7]

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[5] As discussed more in Appendix B and disregarding a potential expansion of all products within a nest, the precise formula is the nest parameter multiplied by 1 minus the revenue share. For example, if the nest parameter is .2 and the cropland has 60% of the total revenue, then the elasticity will be .2 * (1-.6) = .08. This means that a 100% increase in price will cause an 8% change in cropland area.

[6] A parameter on an upper-level nest will then determine the percentage changes in the upper-level nests. Cost/expenditure/revenue shares play a similar role at the upper levels, interacting with the nest parameter to produce a set of computationally convenient results. At the upper level, the relevant price is a price index for the composite commodity.

[7]As examples, the elasticity of substitution in value-added-energy sub-production for many goods is the same for every region. The elasticity of substitution between domestic and imported goods is the same for firms and households, although it is not clear why demand and supply parameters should be equal. The relationship

The land use nest parameters illustrate these problems. To estimate the elasticity of cropland area, and therefore of cropland expansion, the GTAP authors originally relied on a single study, which we call *Lubowski,*[8] focused exclusively on changes in the United States. The use of the *Lubowski* results is a "best case" for GTAP, because this is a respectable, although still imperfect, empirical study. This solely US-focused study generated highly different estimates for different land use transitions in different locations. GTAP boiled down these different elasticities to a single nest parameter for all transitions in all locations and applied this parameter to each type of land transition, in each agroecological zone, and in each of multiple countries or regions (Taheripour, Mueller, and Kwon 2021) (Hertel et al. 2010).

In reality, the relationship between cropland expansion and price will depend on widely different physical conditions in different locations, such as soil qualities, rainfall and slope, as well as economic factors such transportation costs, energy costs, property rights, and differential access to capital. *Lubowksi* modeled detailed *plot-level* transitions, factoring in such variables as soil quality and prior land use. Not surprisingly, *Lubowski* found wide differences in the elasticities that should apply to different plots of land (as well as different elasticities for different types of shift in land uses as discussed below).

The land use nest parameter chosen by GTAP was intended to be an average of these different elasticities in the U.S. Given both the vast physical differences around the world, and the different economics of different land uses in different parts of the world, it would be an extraordinary coincidence if this U.S.-derived parameter could be validly applied to multiple regions and multiple countries.

This is not a correct way to do global analysis. It *is* economically consistent to use globally estimated parameters from global datasets to predict global responses. The biofuel analyses of Roberts and Schlenker (2013) illustrate how this can be done. GTAP-Bio 2010 instead uses local estimates from one country to distill a single parameter that is then applied to many different agroecological zones in many different regions where the parameter interacts with land use data from that zone and region. Doing so is virtually guaranteed to create invalid results as well as a spurious implication of specificity and precision where none is warranted.

Interestingly, the principal GTAP modelers decided in 2013 that applying the *Lubowski* parameter to the whole world was not justified, and they purported to "tune" this elasticity parameter to different regions. But they did not provide any economic analysis for any other

between sources of inputs and the domestic/imported allocation follows the so-called "rule of two." For example, the so-called Armington CES for regional allocation of imports of gasoline is 4.2 and the domestic/imported allocation is one half of that. The CES elasticity of import demand for oil across sources is 10.4, and the CES elasticity between domestic and imported goods is one half of that, and so forth.

[8] Versions of roughly the same empirical study design were published in several versions with different policy applications including (Lubowski 2002), (Lubowski, Plantinga, and Stavins 2006) (Lubowski, Plantinga, and Stavins 2008).

country or region. Instead, they appeared to still use the U.S. parameter as a kind of global, middle benchmark, although it was not. Then, after surveying regions with more or less cropland expansion, the authors subjectively raised or lowered their nest parameter from this benchmark in different regions. They did so without the use of any standard econometric method, most particularly without any attempt to determine if observed land transitions are caused by price changes as opposed to changes in any other determinants of demand and supply. The lack of economic basis is so extreme that the modelers informally chose price elasticity parameters without making use of any systematic data on prices.

Among the resulting alterations, it appears that the GTAP modelers lowered the cropland expansion parameter and therefore elasticity in the U.S. to 10% of the value ascribed to *Lubowski*. Although this U.S.-derived parameter remains the *only* land use change parameter for which the GTAP authors claim to have *any* econometric support, they picked a new U.S. value that contradicted that basis.

Model parameters matter. The lack of empirical support for GTAP is therefore disqualifying all on its own.

In a recent commentary, some GTAP authors claimed that without econometrically derived parameters, it is appropriate to "use a calibration/tuning process to proxy the missing parameters" (Taheripour, Mueller, and Kwon 2021). If there is strong econometric support for a model and its key parameters, it might be appropriate to use a sensitivity analysis to test an unknown parameter. But this model lacks virtually any parameters that are derived from appropriate econometric method applied to appropriate data variation. In this case, appropriate data would include variation in prices, quantities, and in demand side factors that shift demand curves, tracing out land supply. Moreover, the authors are not even using any combination of statistics and data to even roughly "fit" a price-quantity relationship– itself an inappropriate technique. As in the case of double cropping, they appear to be picking parameters to fit a narrative.

3. **The role of revenue shares, which leads to misapplication of these parameters, and contradiction with their underlying economic analyses**

Even if some or all the parameters used in the model had some empirical basis, GTAP changes their meaning by misusing them to project wildly different relationships. That is because, as discussed, all the demand and supply elasticities in GTAP, which govern the supply and demand changes, are determined also by the share of costs or revenues each product or input has within each "nest." This feature was presumably selected because this cost share data is relatively easily available, which may be fine for a research project, but not in a serious policy realm. Its use to determine elasticities, which has large consequences, both lacks an empirical basis and contradicts the limited economics cited by the modelers.

A cake recipe can help illustrate both how a revenue share formula works and why it cannot in general be used to replace empirical estimates of how demand or supply for specific products or inputs varies with price. Baking a cake may require flour, milk, butter, eggs, granulated sugar, powdered sugar, chocolate or vanilla, salt, sprinkles, and baking powder Increased use of some of these ingredients may be able to partially compensate if others increase in price, but that will depend not only on the price of each but on the physical role each plays. For example, a baker might be reasonably willing to substitute powdered sugar for granulated sugar. But given the special need for baking powder, it is unlikely that increasing its cost would cause bakers to use less per cake baked. That is particularly true given the modest contribution to the total costs of a cake of a tablespoon or two or baking powder. With a high enough price increase, it is conceivable that a baker might substitute more egg white to generate the rising effect, but other ingredients probably cannot be substituted at all.

As this example illustrates, demand and supply responses in general depend on a variety of functional attributes and consumer preferences that are specific to those products, inputs, and various alternatives. Consumers will more readily substitute green beans for broccoli than lard. Producers will more readily substitute internet-based news for a newspaper than a massage, although all may be characterized as services. In none of these examples is the overall share of the cost necessarily a single factor let alone a determinative factor in determining these substitutions.

However, under the basic structure of the GTAP model, if the ingredients for a cake are put into the same nest, and the price of baking powder rises, the percentage share of each other cake ingredient will determine what is substituted. As a result, if the price of baking powder rises, GTAP would predict that consumption of baking powder will decline and will be replaced by at least some of *all* the other ingredients. Moreover, the ratios of quantities of the other ingredients replacing baking powder will be based solely on their cost shares. As a result, milk, butter, and chocolate would likely be the largest replacements, in proportion to their cost shares, even though their functional roles are distinct.[9]

Cakes are not specifically in GTAP, but this revenue-share (or cost-share) function is key to determining the elasticity of demand or supply for all products and all inputs. For example, if demand for cropland and therefore its price increases, the quantity of cropland expansion will depend on a nest parameter, but also on its revenue share. And in general, the level and type of substitute inputs (the diversion ratios) will depend exclusively on their relative revenue shares.

Appendix C uses the energy sector to illustrate how this structure leads to non-credible, results. For example, as modeled, the ethanol mandate leads to a large price increase for gasoline, producing a decline in the aggregate consumption of gasoline and ethanol. It also causes substantial declines in household electricity use, and consumption of natural gas, coal and oil for uses other than for transportation. The bizarre feature is that consumption of these other energy sources declines even though their prices decline, which should lead to their increased consumption. As explained in the Appendix, these results, which contradict economic

[9] The formal way to discuss these "patterns of substitution" is as a "diversion ratio," as in the land "diverted" from alternative uses to corn land when the return to corn land increases. See Conlon and Mortimer (2021). In the CES/CET functions of GTAP, within-nest diversion ratios do not depend at all on any parameter, but only on revenue/expenditure shares.

sense and do not seem to have actually occurred, are driven by the structural form of the model, i.e., in the expenditure share assumption together with the multi-level tree structure of the nests.

This theory that revenue or expenditure shares determine elasticities also *contradicts* the few economic analyses cited to generate parameter inputs and results in invalid use of their parameters. Again, GTAP claims that the elasticities governing shifts between cropland, pasture and forest – the prices at which land shifts from one use to another --- are based on each land use's share of the total revenue of all land uses within each agroecological zone. To provide parameters for these shifts, the authors rely exclusively on *Lubowski*. However, that study found that elasticities vary with soil and prior land use, <u>not</u> with AEZ level revenue shares.

An analogy helps to explain the nature of the error. Consider a careful, data-based study of a health treatment that finds success varies with weight. The results might imply that the treatment should only be applied to higher weight people. Now consider a new researcher who has constructed a model that, without evidence, varies treatment success with height. This researcher could (but should not) fit an average treatment effect to people of all heights that matches the average effect found for people of all weights. This researcher could then say, "my model uses the results of the earlier treatment/weight study," but that would be misleading. The interactions with height were purely invented. This new model could not validly be used to advise people to obtain treatment based on their heights.

As described more precisely in Appendix B, the GTAP modelers have engaged in this kind of statistically invalid effort to convert elasticities found using one kind of relationship to project changes based on entirely different relationships, i.e., changes based on revenue share. This is true for shifts among land but also true for all, or nearly all, other statistical relationships in the model.

How the Model Structure and Assumptions Lead to Physical Impossible Economic Projections and Low ILUC Estimates

This section focuses specifically on the effects of this model structure and choice of parameters on the land functions in GTAP. This function plays a key role in determining how much cropland expands and whether that expansion occurs into pasture or forest.

1. GTAP economic functions commonly destroy or create land, and GTAP then uses an artificial constraint to adjust land area in ways that greatly reduce ILUC and further lower conversion of forests.

Because land area is fixed, a land use model needs to be able to determine if cropland expands and how much of this land area comes from each alternative land use, such as pasture and forest. GTAP, however, does not actually base its economic function for allocating land on physical land areas and as a result it can (and will) create or destroy land.

The reason is that the competition between different land uses, such as cropland, grasslands, and managed forest, is represented by their share of their combined revenue within an agroecological zone. When there is a shock to the system, such as more demand for cropland for biofuels, roughly speaking, not the physical areas but the revenue from changes in pasture and managed forest need to match the revenue increase from cropland. Because each acre has a different rent, the physical areas do not match. Depending on the different price changes and other characteristics in different agroecological zones, the model "creates" physical land or "destroys" it. As shown in Appendix A, this features results in vast discrepancies. The changes in total land area are several times larger than the projected changes in cropland area.

One fundamental problem with GTAP is therefore that a viable economic model of land use change cannot create or destroy total land. This is not an insignificant technical discrepancy. The economic theory of the model is that substitutions depend on revenue shares. If the resulting model claims that land is created or destroyed, the economics are incorrect.

The second problem is how the remainder of the model responds to these economic claims. To deal with this problem of fictionally created or destroyed land, GTAP modelers have added a pure adjustment factor, which reduces or increases the area of pasture and forest automatically to match the real physical area. Such an arbitrary adjustment does not make the model economically valid. If a model claims that individual incomes increase in total vastly more than the total national income increases, it is not a sign of a valid model that the model then imposes an adjustment to reduce individual incomes proportionately to match the national income.

In addition, the adjustment factor applied by GTAP generates results that are inconsistent with its economics and result in less forest conversion and a lower ILUC. In Appendix A, we show the results before and after final adjustment of the GTAP model for the U.S. using the 2010 model version of GTAP-Bio for corn ethanol:

- As shown in Table A3, the economic projections in the model in the U.S. are for a total of 7,952 million tons of CO_2 emissions from land use change, but these shrink to 536 million tons with the adjustment (7% of the "economically" estimated ILUC).
- While the economic portion of the model projects that 54% of the non-cropland converted to cropland comes from forest, Table A2 shows this share shrinks to 34% after the adjustment. In other words, the adjustment does not just reduce total ILUC area, but it also sharply reduces the relative contribution of forests to supplying new cropland.
- In several agroecological zones, including AEZ7, which has the largest U.S. quantity of cropland expansion, the model shifts the forestry results and transforms a large decline in forestry area into an increase.

To summarize, the structure of the economics of the model produces physically impossible results. Even if the economics were reliable, the imposed adjustment factor generates an inconsistent result and lower ILUC.

2. GTAP cannot allow conversion of unmanaged land, and thereby forces intensification and demand reduction versus agricultural land expansion.

Previous commentary on GTAP has noted that it cannot model and does not allow conversion of unmanaged land. Unmanaged land can be a large part of a country's agricultural region, and its conversion is a major focus of global agricultural land expansion. Making unmanaged available for conversion would roughly double the potential area of forest that could be converted in GTAP (Plevin et al. 2022). It is difficult to imagine how a model that does not allow conversion of unmanaged land can be used to calculate ILUC. Not surprisingly, using a different model, modelers have found that incorporating unmanaged land leads to a substantially larger ILUC (Plevin et al. 2022).

The significance of this gap in GTAP will even more depress ILUC because the lack of unmanaged land also leads to more limited conversion of grassland and managed forest. In effect, grasslands and managed forest exist in GTAP only to supply livestock or wood products. Yet under GTAP, if increased crop prices were to encourage cropland conversion of these lands, livestock products and wood products cannot be alternatively supplied by expansion into unmanaged land. If cropland begins to expand into grassland, the only options are: (a) for livestock production to be intensified to replace the meat produced; (b) for meat consumption to decline, or (c) for pasture to replace "wood-producing land" not unmanaged land. In turn, for wood-producing lands, the only options are (a) intensification, which the model does not count as causing emissions, (b) a decline in wood consumption, or (c) for wood-producing lands to replace pasture elsewhere. Of these six options, five cannot cause ILUC emissions and one actually reduces ILUC emissions.

In effect, because the model does not allow people to bring more land into human use, the model will structurally favor cropland responses that do not cause ILUC. Then, because of the inability of wood production or livestock production to expand into more unmanaged land, the model will project increases in the profitability of grassland and managed forest. These price increases will further push back against cropland expansion according to essentially the same formula that causes cropland to expand. None of this is based on economic analysis but flows from the unwarranted assumption that only land with a rent can be converted and that its conversion depends on its revenue share.

In short, the model structure both makes it impossible for cropland to expand into unmanaged land, which is much of the concern with land use change, and artificially reduces the conversion of grassland and managed forest.

3. **The revenue share formula requires parameter choices that reduce conversion of forest and conflict with the sole economic source of this parameter.**

The *Lubowski* study, which is the sole, claimed economic basis for land conversion elasticities in GTAP, not surprisingly found that increases in cropland profitability had a far larger effect on conversion of noncropland than increases in the profitability of forest had on conversion of cropland to forest. In fact, the study found that even a doubling of the profitability of forest caused only “extremely small” changes in forest area (Lubowski 2002). (This can be seen visibly in Appendix B.) The reason is intuitive. Wood production and therefore forest “rents” are much lower than cropland rents (Lubowski 2002), so it takes much larger increases in the profitability of forestry to displace cropland than the price increases required of cropland to replace forest. As a result, any viable model, and specifically any model based on the results of *Lubowski*, should have lower elasticities for changes in managed forest area to changes in the profitability of forest than the elasticities the model has for changes in cropland area in response to changes in the profitability of cropland.

But GTAP requires that the same nest parameter that is used to estimate how much cropland expands into other lands with a change in price of cropland also controls how much other land expands into cropland with a change in the price of other land. To provide this single parameter, the GTAP authors chose a parameter that averages the elasticities of the different land uses. (Appendix B provides a more specific description.) As a result, GTAP deliberately chose a parameter that simultaneously understates the elasticity of conversion of cropland and overstates the conversion of cropland to forestry multifold. This means that relative to the findings of Lubowski, cropland will not expand as much in GTAP. It also means that GTAP will overestimate the rebound effect that curtails cropland expansion by overestimating the effect rising wood prices have on resisting cropland expansion.

In short, the functional form causes GTAP to fundamentally misuse the results in *Lubowski* leading to far less forest conversion than the *Lubowski* results imply and thereby to a misleadingly low ILUC.

4. **Additional, incorrect assumptions about managed forests work together with the revenue-share structure to cause forests to instantly reappear elsewhere and to reduce net forest conversion*.***

Both the inability to convert unmanaged land to other uses, including wood production, and the misuse of *Lubowski*’s parameters lead to a strong need to preserve the existing area of managed forest to maintain wood production. Adding to this effect is the assumption that wood production lost due to conversion of managed forests cannot be replaced just by cheaply harvesting more wood from existing managed forests, resulting in additional carbon losses. In the real world, managed forests are growing, in significant part due to higher carbon dioxide fertilization and other aspects of climate change itself (Harris et al. 2021) (Pan et al. 2011) (Ruehr et al. 2023). Forests have abundant more wood that can be harvested, which means that they can supply more wood – with a carbon cost not counted in GTAP – to replace any wood supplies lost by conversion of some managed forests to cropland.

These limitations of the GTAP structure work together not only to resist forest conversion but also to a "rebound" of agricultural land to forests. In other words, if some forests are converted to agriculture in one agroecological zone, new managed forests can reappear at the expense of agricultural land in another US zone. This is not based on any actual economic estimates – and is contradicted by the estimates in the *Lubowski* analysis that even a doubling of the profitability of forest has "extremely small" effects on forest area (Lubowski 2002).

5. How inappropriate modeling of international trade limits GTAP's projection of U.S. biofuel consumption on world land use.

In Appendix D, we discuss the GTAP trade model. This model is based on a late 1960s idea that trade patterns in manufactured goods can best be explained by a "home bias" for domestic products. GTAP applies such a model to world agricultural trade. As explained in this Appendix, this structure goes against a large, high-quality, empirical literature that there is a well-integrated world market for homogeneous agriculture products, without home bias, limited only by transportation costs. An implication of this literature is that cross-country price differences for core agricultural commodities are severely limited by cross-country arbitrage, constrained only by (relatively low) transportation costs. GTAP does not impose this arbitrage constraint, instead allowing the modeled "home bias" to limit trade.

The empirically contradicted GTAP trade model forces much of the adjustment to U.S. biofuel policy to remain in the US. The model can predict very large changes in U.S. crop prices that are not matched by changes in other countries. This then forces much of the equilibrium adjustment onto predicted U.S. consumption and U.S. livestock intensification. A realistic model of world trade could easily predict that much more of the adjustment would take place outside of the US, particularly along active forest/crop boundaries, as in the well-measured empirical papers cited in the introduction.

Summary

In summary, we find that GTAP lacks an economic basis, is peculiarly unsuited to estimate changes in land use, and systematically and without economic foundation leads to low ILUC estimates:

- Of thousands of parameters, only a few are claimed to have any credible economic foundation for the products and locations to which they are applied. Even these parameters that are referenced by the model are misapplied. Most importantly, they are claimed to project economic changes based on revenue or cost shares, which has large consequences, even though the original empirical studies made no such projections.

- The structure causes the model not to allocate land but to create or destroy large quantities of land relative to changes in cropland, which makes it not credible for analyzing land use change. A subsequent "hand-of-God" readjustment is required to conserve physical land area. This adjustment both greatly reduces ILUC estimates and reduces the role of deforestation – and therefore its high emissions - in contributing to additional cropland.

- The structure of the model, including its unsupported use of revenue and cost-shares, leads to low ILUC.

    - The structure prevents GTAP from allowing conversion of unmanaged land, which includes roughly half of all forests and is a major focus of global land use change. The inability to convert unmanaged land in turn leads the model to project increased profitability of managed forest and pasture, which limits their conversion to cropland.
    - The structure requires GTAP to select a single parameter for each nest, which resulted in a parameter that understates the expansion of cropland in response to price increases and vastly overstates the role that increased profitability of forestry has in resisting conversion to cropland or pasture.
    - The structure does not model standing forests and so requires an assumption that all "forestry land" is currently fully engaged in the production of wood. If forestry land is converted to cropland in one zone, this creates pressure to create forestry land in other zones to meet the continuing demand for wood. In the model, these new "forests" do not even need to grow and mature; rather they instantly appear.

- The trade model, borrowed from non-agricultural markets and without econometric support, underestimates the role that trade in agricultural goods leads to similar changes in crop prices across countries and thereby leads to large underestimates of the global land use change from U.S. changes in biofuels.

- More recent changes to the model, also without economic support, further lower ILUC in a variety of ways. One assumes, in contradiction to experience in the U.S., that most of the new cropping area is supplied by increases in double cropping or other cropping intensity. Another assumes a large, unjustified response of pasture-intensification to grassland conversion, which greatly reduces the need for pasture to expand into forest to maintain meat and milk production if other pasture is converted to cropland. A third change greatly reduces the carbon losses associated with conversion of pasture.

Many of these unjustified effects work together to generate an extremely low ILUC. Several effects cause the economic component of the model to select conversion of grassland rather than forest. The ad hoc adjustment at the end then further reduces the role of forest conversion relative to grassland. The pasture intensification function avoids the pressure to clear forest to replace pasture converted to cropland. After these factors combine to limit forest conversion, the claim that much of the grassland conversion to cropland increases soil carbon makes the remaining conversions carbon "cheap."

In Taheripour et. al. (2021), the GTAP modelers do not claim to have significant econometric support for the model but contend, in effect, that it is appropriate to assume a model structure and most of the parameters and then adjust it to data. That is incorrect. Across the sciences, particularly those that cannot use direct experiments, there has been widespread attention to statistical abuses. Economics went through a credibility revolution in which even otherwise valid regressions were shown to be improper because they did not use "instruments" to separate correlations from causal effects (Angrist and Pischke 2010). But the calibration exercise the GTAP modelers are employing – many that involve ad hoc adjustments to parameters -- are not even making statistical errors because they are not using statistics to try to explain the effects of changed prices. They are at best assuming some stories to explain what is happening in the world and then altering parameters to fit their assumed stories. This effort is illegitimate: it is always possible to use different stories to explain the data, with different implications for the role of biofuels or any other source of increased demand.

Economics requires more. As shown, GTAP is generating results that project the lost carbon from land to generate additional crops for biofuels is only a very small fraction of the average carbon lost to produce these crops in the past. Only with these large reductions in ILUC can a model even project greenhouse gas reductions from these biofuels relative to using fossil shows. By contrast, as shown in Table 1, using this average carbon loss would indicate that crop-based biofuels do not come close to reducing greenhouse gas emissions from transportation over 30 years. This average from experience should not be disregarded absent sound economic evidence to the contrary.

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Appendix A: GTAP-Bio's Projections of Changed U.S. Land Use and ILUC Projections with and Without Adjustments

This appendix shows results from the GTAP-Bio 2010 ethanol expansion policy experiment. The columns are U.S. agroecological zones (AEZs). The columns labeled "With Adjustment …" are the reported land use changes. These are given in percentage terms in Table A1 and in physical terms in Table A2. The U.S. does not have the full set of AEZs, so while GTAP produces "percentage changes" for zones that do not exist in the U.S., they correspond to no physical change in land. The three columns labeled "economic predictions" are the values net of the ad-hoc adjustment. These are not equilibrium outcomes as defined in the model, but they are the "economic output" of the model, to which the adjustment is applied. In Table A1, we see that forestry and livestock land are arbitrarily reduced by the same number of percentage points. The cells in red represent cells where the adjustment causes projections of forest area decline by the economic model to turn into forest area increases after the adjustment. The table further shows how the model does not allow changes in unmanaged land.

Table A1.

Non-Market Ad-hoc Adjustment vs Economic Predictions in the GTAP-BIO Model (in % Change)

	With Adjustment in the Model				Economic Predictions				% Adjustment (Differences)			
	Forestry	Livestock	Crops	Unmngland	Forestry	Livestock	Crops	Unmngland	Forestry	Livestock	Crops	Unmngland
AEZ1	-0.50	-1.13	1.66	0.00	-2.37	-2.99	1.09	0.00	1.86	1.85	0.57	0.00
AEZ2	-0.50	-1.13	1.66	0.00	-2.37	-2.99	1.09	0.00	1.86	1.85	0.57	0.00
AEZ3	-0.50	-1.13	1.66	0.00	-2.37	-2.99	1.09	0.00	1.86	1.85	0.57	0.00
AEZ4	-0.50	-1.13	1.66	0.00	-2.37	-2.99	1.09	0.00	1.86	1.85	0.57	0.00
AEZ5	-0.50	-1.13	1.66	0.00	-2.37	-2.99	1.09	0.00	1.86	1.85	0.57	0.00
AEZ6	-0.50	-1.13	1.66	0.00	-2.37	-2.99	1.09	0.00	1.86	1.85	0.57	0.00
AEZ7	0.34	-0.30	1.15	0.00	-2.39	-3.00	1.38	0.00	2.72	2.70	-0.23	0.00
AEZ8	0.16	-0.48	0.56	0.00	-3.23	-3.84	0.53	0.00	3.38	3.36	0.03	0.00
AEZ9	-0.05	-0.69	0.30	0.00	-4.51	-5.12	0.23	0.00	4.46	4.43	0.07	0.00
AEZ10	-0.41	-1.04	0.86	0.00	-5.01	-5.61	0.67	0.00	4.60	4.57	0.18	0.00
AEZ11	-0.39	-1.02	0.85	0.00	-4.35	-4.95	0.75	0.00	3.96	3.93	0.10	0.00
AEZ12	-0.25	-0.88	1.34	0.00	-1.93	-2.55	1.46	0.00	1.69	1.68	-0.12	0.00
AEZ13	0.15	-0.49	0.75	0.00	-1.19	-1.82	0.98	0.00	1.34	1.33	-0.23	0.00
AEZ14	0.01	-0.62	1.86	0.00	-1.34	-1.96	2.15	0.00	1.35	1.34	-0.29	0.00
AEZ15	0.00	-0.63	2.60	0.00	-1.34	-1.97	1.70	0.00	1.34	1.33	0.90	0.00
AEZ16	-0.00	-0.64	2.74	0.00	-0.10	-0.73	3.20	0.00	0.10	0.10	-0.46	0.00
AEZ17	-0.50	-1.13	1.66	0.00	-2.37	-2.99	1.09	0.00	1.86	1.85	0.57	0.00
AEZ18	-0.50	-1.13	1.66	0.00	-2.37	-2.99	1.09	0.00	1.86	1.85	0.57	0.00

Note: The values in the table are presented in percentage terms.

Table A3 (on the next page) applies the GTAP land use changes in CO_2 emissions to the physical land changes in Table A2. These changes are dramatic. The "hand of God" adjustment turns large CO_2 emissions from forestry land destruction into small positive or negative changes in $C0_2$. For U.S. ILUC, the arbitrary adjustment factor has large effects on the predicted results.

Table A2

Non-Market Ad-hoc Adjustment vs Economic Predictions in the GTAP-BIO Model (Level Changes from Baseline)

	With Adjustment in the Model				Economic Predictions				Adjustment in Levels			
	Forestry	Livestock	Crops	Unmngland	Forestry	Livestock	Crops	Unmngland	Forestry	Livestock	Crops	Unmngland
AEZ1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AEZ2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AEZ3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AEZ4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AEZ5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AEZ6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AEZ7	0.03	-0.43	0.41	0.00	-0.19	-4.33	0.49	0.00	0.21	3.90	-0.08	0.00
AEZ8	0.02	-0.18	0.15	0.00	-0.49	-1.42	0.15	0.00	0.52	1.24	0.01	0.00
AEZ9	0.00	-0.04	0.04	0.00	-0.44	-0.28	0.03	0.00	0.43	0.24	0.01	0.00
AEZ10	-0.26	-0.17	0.43	0.00	-3.14	-0.94	0.34	0.00	2.89	0.76	0.09	0.00
AEZ11	-0.20	-0.12	0.32	0.00	-2.25	-0.58	0.28	0.00	2.05	0.46	0.04	0.00
AEZ12	-0.16	-0.06	0.22	0.00	-1.23	-0.18	0.24	0.00	1.07	0.12	-0.02	0.00
AEZ13	0.02	-0.04	0.01	0.00	-0.19	-0.14	0.02	0.00	0.21	0.10	0.00	0.00
AEZ14	0.01	-0.01	0.01	0.00	-0.75	-0.04	0.01	0.00	0.76	0.03	0.00	0.00
AEZ15	0.00	0.00	0.00	0.00	-0.68	0.00	0.00	0.00	0.68	0.00	0.00	0.00
AEZ16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AEZ17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AEZ18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	-0.54	-1.05	1.59	0.00	-9.35	-7.91	1.55	0.00	8.81	6.85	0.04	0.00

Note: The values in the table are presented in million hectares.

Table A3

Non-Market Ad-hoc Adjustment vs Economic Predictions in the GTAP-BIO Model (in CO2 Emissions)

	With Adjustment in the Model				Economic Predictions				Adjustment in Levels			
	Forestry	Livestock	Crops	Unmngland	Forestry	Livestock	Crops	Unmngland	Forestry	Livestock	Crops	Unmngland
AEZ1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AEZ2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AEZ3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AEZ4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AEZ5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AEZ6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AEZ7	-5.74	45.96	-7.33	0.00	141.61	459.07	-8.78	0.00	-147.35	-413.10	1.45	0.00
AEZ8	-5.22	18.79	-2.76	0.00	375.99	150.35	-2.62	0.00	-381.21	-131.57	-0.14	0.00
AEZ9	3.77	3.99	-0.77	0.00	331.58	29.77	-0.59	0.00	-327.81	-25.78	-0.18	0.00
AEZ10	194.05	18.38	-7.72	0.00	2386.75	99.31	-6.08	0.00	-2192.71	-80.92	-1.64	0.00
AEZ11	154.42	12.68	-5.81	0.00	1708.66	61.31	-5.13	0.00	-1554.24	-48.63	-0.68	0.00
AEZ12	118.33	6.57	-3.92	0.00	931.92	19.10	-4.28	0.00	-813.59	-12.53	0.36	0.00
AEZ13	-4.96	3.89	-0.25	0.00	141.43	14.45	-0.33	0.00	-146.40	-10.56	0.08	0.00
AEZ14	-1.54	1.39	-0.11	0.00	571.93	4.39	-0.13	0.00	-573.47	-3.00	0.02	0.00
AEZ15	-0.06	0.09	-0.01	0.00	514.30	0.29	-0.01	0.00	-514.36	-0.20	0.00	0.00
AEZ16	0.02	0.00	0.00	0.00	3.61	0.00	0.00	0.00	-3.58	0.00	0.00	0.00
AEZ17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AEZ18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	453.07	111.74	-28.68	0.00	7107.79	838.04	-27.94	0.00	-6654.72	-726.29	-0.74	0.00

Note: The values in the table are presented in million Mg CO2 Emissions.

Appendix B: How GTAP Transforms *Lubowski* Land Use Transformation Elasticities to GTAP Parameters and the Resulting Inconsistencies

The ways in which GTAP uses the estimated elasticities from Lubowski (2002) can be seen in graphs taken from the GTAP working paper (Ahmed, Hertel, and Lubowski 2009), which are reproduced below. Lubwoski (2002) used a functional form that estimated different elasticities over different years, in other words, it estimated that land use conversions would occur more over time. The GTAP authors decided to use the estimated elasticity after 5 years. As can be seen in what the Ahmed paper labeled Figure 2, the percentage change in the area of forest in response to changes in forestry's own profitability is extremely small. By contrast, the response of cropland area to a percentage change in the price of cropland is many times larger. In other words, for the same percentage change in their own profitability, cropland should expand by a much larger percentage than forestry.

Figure 3 shows how GTAP translated this "own price" elasticity into the very different transformation elasticities used in GTAP, which we have called "nest parameters," and which the GTAP authors call CET values. These "nest parameters" contribute to but are not themselves elasticities in GTAP. Those elasticities depend both on the nest parameter and on the share of revenue each land use type has in each agroecological zone in each country or group of countries. The formula for the ultimate elasticity is this nest parameter multiplied by one minus the revenue share of that land use. For example, if the nest parameter is 0.2 and cropland in an AEZ has 60% of the revenue, the elasticity would be 0.2 * (1-.6), which equals 0.08. Running GTAP for the U.S., the authors determined the average nest parameters values (CET values), for each of the three different land uses (cropland, pasture/range and managed forest). These are the CET values that result in the relevant elasticity predicted by *Lubowski* for that land use. Figure 3 shows that the matched nest parameters are very different for the different land uses, with particularly large differences between managed forestry and pasture or cropland. The authors chose a roughly average parameter of the three different land use types at the period of 5 years, or 0.2. They did so because the GTAP function requires that the same parameter be used for all items, such as all land uses, in the same nest.

As discussed in text, this approach has two fundamental flaws that both ensure the predictions of GTAP will not actually match those implied by *Lubowski* (2002), the claimed source, and that they will result in far less conversion of forest. One flaw is simply that the resulting CET value will result in wildly different elasticities for different land uses and in different agroecological zones and countries based on their different revenue shares. Yet *Lubowski* (2002) did not find that elasticities vary by revenue share. The GTAP function is therefore not just inconsistent but contradicts the findings in *Lubowski* even as it purports to base the model on *Lubowski.*

The second flaw is that this approach greatly overestimates the elasticity of managed forest, which leads to a strong underestimate of conversion of forest and underestimate of cropland conversion. The reason an excessive forestry elasticity also reduces cropland expansion is that the model predicts increases in the price of managed forest due to some loss of forest area, and then, as forestry prices increases, this excessive elasticity will cause the model to over-resist net conversion of forest to cropland. As discussed in text, this excessive own price forest elasticity, which is far beyond the elasticity found in *Lubowski*, will also cause forests to expand in other agroecological zones at the expense of cropland.

Figure B1 – Figures taken from Ahmed et al. (2008) showing how GTAP derived its transformation parmaters from Lubowski (2002)

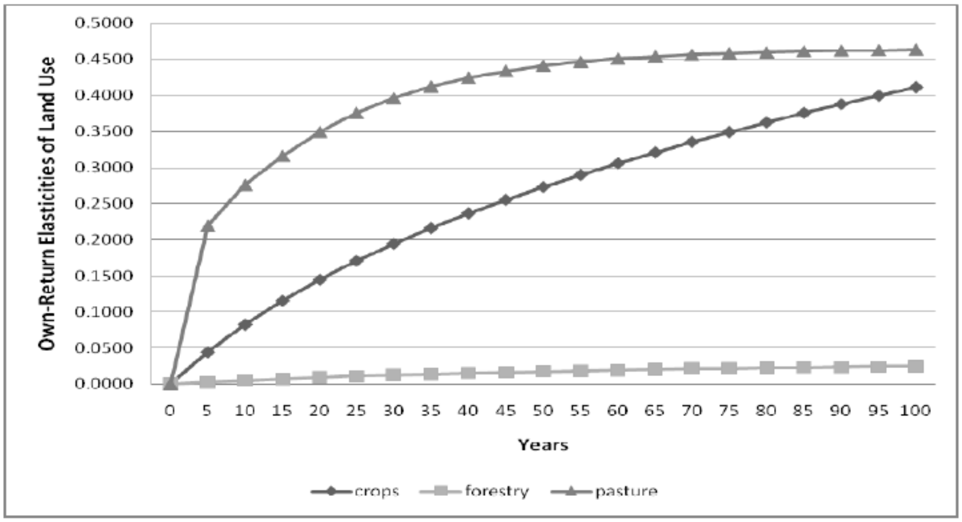


Figure 2: Own-Return Elasticities of Land USe at *t* for Use *i*
Source: Authors' Simulations

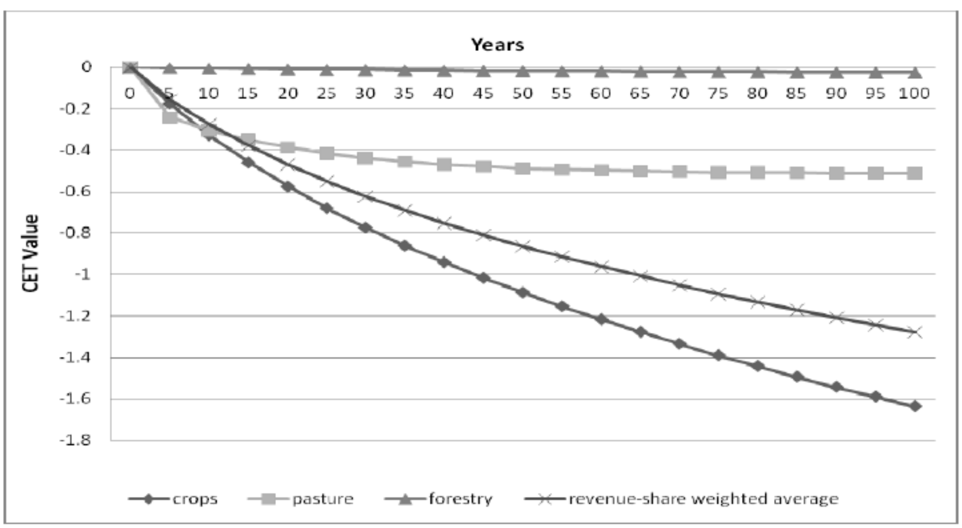


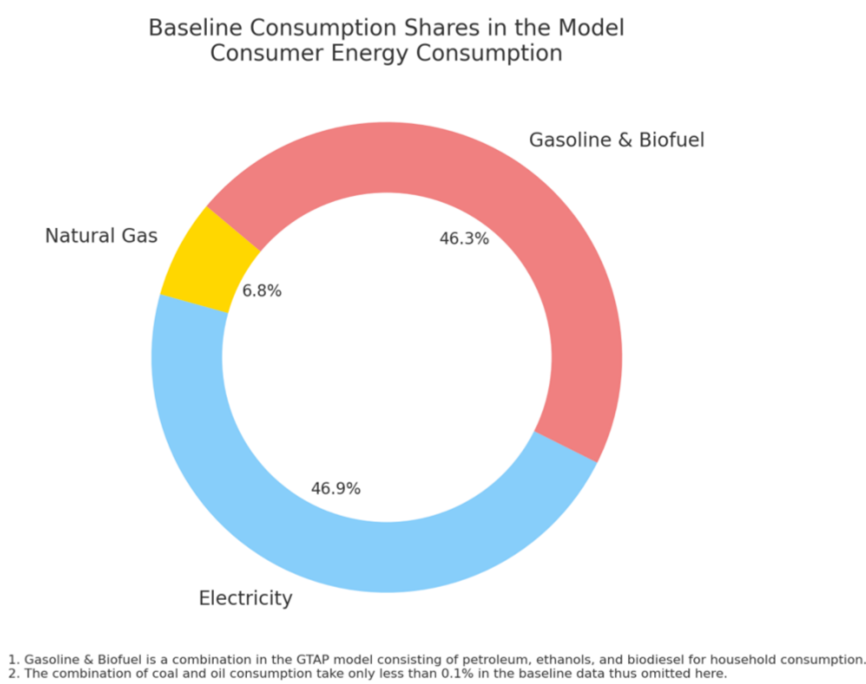
Figure 3: CET Calibration Estimates by Land Use at time *t*, for t=5 to t=100
Source: Authors' Simulations

Appendix C: Example and Discussion: Household Energy Consumption and the Counterintuitive Effects of the GTAP Model Structure

Examining projected changes in household energy consumption due to ethanol serves as a pedagogical exercise to understand the structure of GTAP, and illusetrates how GTAP can generate counterintuitive results that likely bear little resemblance to reality. The result is most counterintuitive because the model projects household electricity consumption to fall, even as it projects declining electricity prices that should cause its consumption to increase. The reason lies in the choice of nesting structure for household energy and its interaction with the expenditure-share formula, which are hard for policy makers to understand.

The following figure displays the GTAP-Bio (2010) data on baseline household energy expenditure shares in the in base year of the model.[10] “Gasoline and Biofuel” is an aggregate created by a lower-level nest from a combination of gasoline and biofuels. As noted, quantities and types of energy substituted are determined by these expenditure shares and do not even depend on the nest parameter. This result means that the structure of the model will automatically create a large substitution effect if a policy changes the consumption of the gasoline-biofuel bundle.

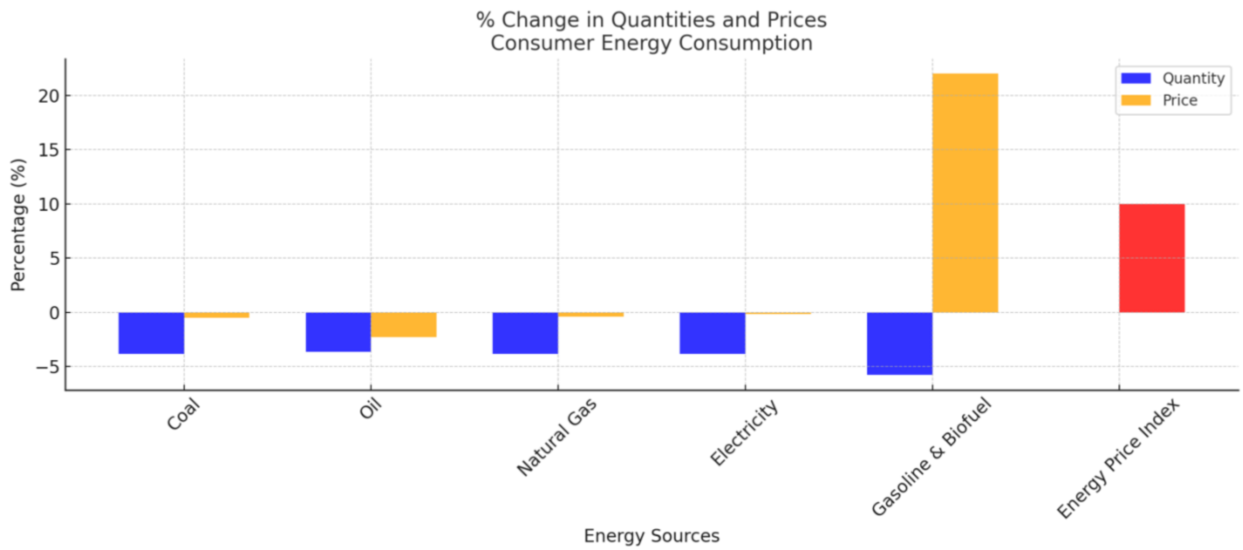
Figure C1.



[10] We frequently rely on the 2010 version of GTAP-Bio because it is by far the best documented version of the model. We have verified that most key features remain in place in a later CARB version of the model, although some components of the overall model are further elaborated by CARB.

The result of the GTAP ethanol policy simulation exercise is shown in the following figure. (It reveals market prices before taxes.)

Figure C3.



Gasoline & Biofuel is a combination in the GTAP model consisting of petroleum, ethanols, and biodiesel for household consumption.

We see that the price of the gasoline-biofuel bundle is predicted to increase by over 20%. This causes the use of the combination of gasoline and biofuel to drop by more than 5%. Surprisingly, though, the consumption of household electricity and natural gas falls by more than half as much in percentage terms. One can see in the graph that these startling effects are not caused by a rising price for non-gasoline energy; in fact, they decline. We know of no attempt in the GTAP modeling community to validate their predictions that ethanol policy will cause the consumption of natural gas, fuel oil and electricity to decline without any price increase in these energy sources to motivate a decline.

It turns out that these odd results are caused by a combination of (1) the simplified way that GTAP models ethanol policy and (2) the use of a particular price index to model overall household energy consumption. The second effect, the use of special nest price indices, has important effects throughout the GTAP model.

On the first point, the modelers assume a target level of corn ethanol use (a more than 750% increase over pre-policy levels) and assume that this will be achieved via a consumption subsidy to corn ethanol. In the model, the subsidy is paid for via a tax on gasoline.[11] This is contrary to reality, but the modelers can only do simple policy exercises. They require that

[11] The choice of how to simplify a policy (and other exogenous factors) inside of GTAP is called the "closure" of the model. Discussion of model predictions are rarely related back to the decisions made about the closure, even though the choice of the closure can have large effects on policy outcomes.

government policy is budget-balanced, so the subsidy has to be offset by some tax. In the GTAP computation, the required taxes and subsidies are very large.

This artificial policy then interacts with the very structure of the model to create the odd (and very likely incorrect) results. In GTAP, a higher-level nest determines consumer expenditure on the dollar-valued “household energy bundle.” The consumption of this bundle is driven by a single price index. The percentage change in this price index is calculated as a weighted average of the percentage price changes across all the products in the nest. The weights are the fixed base-year expenditure shares displayed in the prior chart.

Since gasoline is a large part of the energy bundle, the predicted increased price of gasoline drives up this price index, as shown in the red bar of the last chart. Figure C3 shows see that the overall “price of energy” is now 10% higher. In the GTAP structure, this price increase causes a decrease in the fictional “energy composite,” which drives down the consumption of all energy. That sounds reasonable overall, but the strange result occurs because the GTAP structure simply distributes this declining energy consumption across all the energy products, even those with declining prices. It thereby causes consumption of these alternative energy products to decline even as decreases in their prices should motivate consumers to increase their consumption.

Appendix D. The GTAP Trade Model

As noted elsewhere in our report, there is strong empirical evidence of a moving cropland frontier in some places in the world. Given world trade in agricultural products, this means that diverting corn production to ethanol in the US will likely result in land use changes along these more active non-US land use frontiers. The GTAP model was originally built as a trade model, and it contains a complex model of these effects.

Over decades, the GTAP -BIO approach to trade has been rendered obsolete in the academic literature. New trade models (e.g. Eaton and Kortum (2002) and Adao, Costinot and Donaldson (2017)) are explicitly motivated by a desire to avoid the problems of models with thousands of poorly justified parameters. These new trade models feature product differentiation, imperfect competition and, above all, a key role for the effects of distance and market size (the empirically impressive “gravity” model of trade). This is very different from GTAP.

GTAP has parameters that reflect a strong “home bias” in consumption. This reflects, for example, the traditional tendency of French consumers to buy French cars while German consumers buy German, but not French, cars. The home bias effect is motivated by trade in manufactured goods and certain kinds of services. However, there is an important literature that rejects the idea of a large home bias for agricultural products. Shipping distance may still have a strong effect on fresh goods (although these are often shipped very long distances) but likely has much lower effects for non-branded bulk products like grain or food oil. It is difficult to believe that many consumers care intensely about the country-of-origin of the grain or food oil in processed foods.

In contrast to GTAP, Roberts and Schlenker (2013), published in the prestigious American Economic Review with 581 citations, uses rigorous econometric tests to show that Brazilian crop price responses to U.S. corn yield shocks are statistically indistinguishable from U.S. responses to U.S. shocks. This indicates a high degree of world market integration, consistent with the existence of large international companies who are in the business of agricultural commodity arbitrage. This empirical finding conflicts with the GTAP “home bias” assumption that restricts trade in agricultural commodities. Roberts and Schlenker also cite Fackler and Tastan (2008), who develop statistical procedures to test for market integration. They consider the market for soybeans, which they say is well-understood to be integrated. Their statistical tests confirm that "the United States/Brazil/Rotterdam markets appear to be fully integrated" in soybeans.

Berquist et al (2022) argues persuasively that credible policy analysis in agricultural policy cannot rely on GTAP style models (which are a subset of the more general traditional “CGE models”.) That paper criticizes GTAP-style models that “largely abstract from modeling the granular economic geography of farm production, consumption and trade costs” that are key to policy analysis. The paper properly distinguishes trade in homogenous goods like commodity crops from trade in manufacturing goods, for which variations in products like the cars of Renault versus Volkswagen, create loyalties that slow shifts in trade. The paper showed how trade is still influenced by transportation costs that vary with distance, but once cross-location price differences are enough to overcome the transportation cost, new and expanded trade links can be created very quickly.

In (Villoria and Hertel 2011), the authors conceptually defend the GTAP trade model through analysis claiming that data does not prove an integrated world model of prices. Their analysis, which conflicts with papers cited above, is not convincing:

- It does not use any kind of exogenous shock ("instrument") to test market integration. The paper therefore of necessity confuses different supply and demand effects and cannot produce credible empirical results (Angrist and Pischke 2010); (Berry and Haile 2021), (Pearl 2009). By contrast, Roberts and Schlenker (2013) do make use of such shocks, which makes their results showing close price integration far more credible.
- The paper does not reference any modern trade literature.
- Although the paper rejects a theory of one global price, that does not justify use of the GTAP model, which just imposes a restriction for unknown reasons on the degree of shift in trade in response to prices. The alternative to account for differential prices is to factor the effect on prices of real, measured, transportation costs, which is an approach consistent with modern trade theory. The two approaches reach different results. A transportation cost model, with otherwise homogeneous goods such as soybeans, would impose maximum price differences between two points (with the difference being the transport cost). GTAP does not impose these maximum differences, which can result in unrealistic trade barriers because it can allow US prices to rise tremendously more than European or Brazilian prices.

Overall, there is a lack of evidence to support the GTAP approach to agricultural trade and a large well-cited literature that advocates very different approaches. These are important for ILUC. By artificially restraining trade effects in agriculture, GTAP is artificially restricting the effects of biofuel policy to the U.S. Because the crop/forest frontier is more settled in the U.S. than elsewhere, and because quickly expanding trade links are plausible, this trade feature will underestimate the world-wide land use changes.