Biofuels, Deforestation, and the GTAP Model

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Abstract

Increasing use of biofuels increases the demand for agricultural land. Credible empirical evidence supports the common-sense judgment that this will lead to the conversion of forests and other habitats to generate more cropland, particularly in the tropics, where land conversion is cheapest. However, when analyzing the effects of biofuels on land use, governments frequently use a particular class of economic models, including the popular "GTAP" model, to justify a finding that biofuels will cause little additional land conversion. We argue that the GTAP model does not provide a credible scientific basis for this conclusion because it lacks an econometric basis for its economic parameters, and generates physically impossible results by a wide margin. It also incorporates several unsupported assumptions that guarantee little land use change, such as constraints on international trade and a failure to account for unmanaged forests.

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Summary

As the global population and incomes grow, increasing demand for food creates economic pressure to expand agricultural land, which replaces forests and woody savannas with cropland or pasture and releases large quantities of carbon that significantly contribute to climate change. Around the world, governments are also promoting the large-scale use of biofuels made from crops that also require land. A credible empirical literature describes a clear path from domestic biofuel production to tropical deforestation that likely causes overall increases in emissions. First, it is well accepted that biofuel policies raise domestic food prices; indeed, they are intended to do so. Second, domestic price increases for basic agricultural commodities propagate worldwide via the import/export activities of global commodity traders. Third, tropical deforestation responds to economic incentives such as increased crop prices. Fourth, the average carbon emissions from clearing land to produce the crops that generate biofuels exceed the resulting savings from reduced gasoline or diesel use by 300-400% for at least thirty years.

These empirically established causal paths from domestic biofuel policy to deforestation in the tropics strongly caution against turning food crops into fuel as a climate policy. However, when setting biofuel policy, governments frequently ignore this evidence and instead use a particular class of complex economic land use models. These models purport to predict in a highly disaggregated way how biofuel demand alters the demand and supply of different crops and land uses in many regions throughout the world. Variants of the popular GTAP model are used for this purpose by the State of California, for international aviation agreements, and by the U.S. Treasury for tax credits at least in 2024. Due to a range of market-mediated responses, including reduced food consumption, GTAP claims that diverting crops to biofuels results in little expansion of cropland and even less loss of forests or other carbon-rich land. As a result, governments assume that switching to biofuels reduces greenhouse gas emissions.

Getting biofuel policy wrong is not a minor issue because current global biofuel policies are already a major driver of growth of demand for agricultural products, and emerging policies have the capacity to transform the earth. Between 2004 and 2024, global oilseeds used for vegetable oil expanded by roughly 250 million acres (an area equivalent to roughly three quarters of U.S. harvested cropland), and during this period, biomass-based diesel fuel contributed roughly 40% of the increased vegetable oil demand.[2] Announced projects would more than triple capacity for renewable diesel (Malins and Sandford 2022). Spurred in part by government policies and international agreements, most of the aviation industry has pledged to decarbonize by 2050, and under some policies and international agreements, airlines can use biofuels to claim reduced emissions (Graver et al. 2022). Biofuels from vegetable oils are among the cheapest claimed "sustainable aviation fuels (Graver et al. 2022). If vegetable oils supply even one-quarter of likely aviation fuel in 2050, their production will require 40% of global cropland at today's oilseed mix and yields (Authors' calculations).

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[2] These are authors' calculations from UN Food and Agricultural Organization Data on cropland area, Energy Institute data on biofuel consumption, and OECD estimates of the different sources of biomass-based diesel.

Should governments rely on GTAP-style models to conclude that biofuels will not lead to vast deforestation and benefit the climate? We have been able to analyze and run GTAP code directly and can provide new, direct, and independent evidence of how the model works to produce low ILUC numbers. The GTAP model may be an interesting theoretical research tool for some purposes, but we conclude that it lacks scientific credibility as a policy tool, particularly when applied to biofuels and land use. As summarized on the following page, the model produces physically impossible results by a wide margin. The parameters and equations that dictate its economic effects -- the justification for the model's use -- lack empirical basis. The model also contains multiple pure assumptions that contradict empirical evidence and that independently and even more collectively guarantee a low ILUC.

We argue that governments should replace reliance on GTAP-style models with an alternative, more transparent focus on the opportunity cost of land used for biofuels. This is consistent both with how governments typically model the carbon costs of other kinds of economic activities, from using gasoline to making cars, and with how economists evaluate costs in general: What potential carbon mitigation is lost by using land for biofuels rather than in alternative ways? If not used for biofuels, land can be used to store carbon (in the form of forests). It can also be used to produce food, which not only contributes directly to human welfare but also permits forests and other carbon-rich habitats to remain in their uses and continue to store carbon. Any alternative approach should be consistent with the lack of positive empirical evidence that biofuels will reduce emissions and with the strong empirical evidence linking biofuel use to tropical deforestation.

In this paper, we discuss each of these issues in greater depth. We provide some background information on biofuels, land use, and the existing empirical literature before turning to a more detailed discussion of GTAP modeling.

Summary of Important Problems with GTAP Models

Physically impossible results: The economics in the model do not allocate physical land; instead, they allocate expenditures on the uses of land. This economics results in the creation or the destruction of vast quantities of land. A non-economic "hand-of-God" readjustment is then added to conserve physical land area. Economics that generate impossible results cannot be valid, and the arbitrary adjustment contradicts any economic rationale to use the model. As implemented, the readjustment also greatly reduces the extent of deforestation and ILUC.

Parameters and predictions lack empirical support. An economic model is only as robust as its economic parameters and functions. Although GTAP contains thousands of economic parameters and equations, only a few are even claimed to have a credible empirical basis. Even these few parameters are then invalidly applied out of context. Ultimate supply and demand elasticities, the core of the model's economics, are then often dramatically changed based on "expenditure share" formulas that lack an empirical basis. The resulting elasticities contradict even the few studies cited as their sources.

Purely assumed substitution formulas. Because a major factor in ILUC calculations is which types of lands replace other lands, and which food or feed crops replace other crops, the claim that GTAP predicts these "diversion ratios" is a major justification for its use. But the key driver of these diversion patterns in GTAP is an assumption made solely for ease in operating the model, with no empirical basis at all.

Limited international commodity trade restricts deforestation where it most occurs. Although agricultural expansion is occurring mainly in the Tropics, the GTAP trade model without econometric support greatly limits any contribution of U.S. demand to this expansion. It does so by artificially restricting global trade in agricultural products, which limits the transmission of U.S. demand and price increases to currently deforesting regions. This leads to projections of large price differences in different regions that do not occur.

Inability to convert unmanaged forests. GTAP does not allow any conversion of unmanaged land into managed land. Unmanaged land includes roughly half of all forests and is a primary focus of global land use change. The inability to convert unmanaged land both directly prevents its conversion and has the effect in the model of limiting conversion even of managed forests by increasing their profitability.

Unrealistic yield increases in place of land expansion. GTAP modelers often assume a strong yield response to price, including for pasture, without empirical support and in contradiction of evidence. Evidence shows that even when demand encourages more infrastructure and R&D investments, that can lead to more expansion in carbon-rich and lower-yield locations.

Unsupported recent decisions to further lower ILUC. More recent changes to the model systematically lower ILUC in multiple ways, for example, by simply assuming that most new cropland results from growing crops on existing cropland twice per year. These assumptions are made without economic evidence and even contrary to empirical observation.

Global Agricultural Expansion and Benchmarking Biofuel Indirect Land Use Change

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 (Potapov et al. 2021), roughly equal to the annually harvested cropland area of Iowa. Although data limitations impede analysis of net changes in pasture area, satellites show gross expansion of pasture into forest is an even larger direct source of deforestation than cropland (Weisse & Goldman 2021). Converting forests and other native vegetation to agriculture releases carbon otherwise stored in vegetation and soils, which is estimated to cause around 10% of all human emissions (Searchinger et al. 2023). At this rate, the world would convert an area the size of India to cropland by roughly 2050, while nearly all climate strategies to achieve Paris Agreement targets require no net land expansion, and most require some contraction of agricultural land to allow for reforestation (Searchinger et al. 2023). (See Appendix A for illustrative maps and charts.)

This focus on the *net* expansion of cropland also underestimates the climate costs of agricultural expansion by net factoring in gross cropland expansion. For example, the same cropland satellite study found that gross global cropland is expanding at twice the rate of net expansion because expansion in some areas is offset by the abandonment of cropland elsewhere (Potapov et al. 2021). Because carbon losses are quick and restoration is slower, and because conversion generally occurs in more carbon-rich lands, the losses of carbon over at least several decades will exceed the net losses. In addition, recent research has shown that agricultural expansion is an inefficient process, clearing two hectares for each one hectare that becomes productive agriculture (Pendrill et al. 2022). (Other clearings occur due to speculation, poorly controlled fires, or unsuccessful agricultural use.) These findings suggest that virtually all land use change models are underestimating emissions because they assume that one needed new hectare of cropland results in only one hectare of conversion.

Biofuel policy is fundamentally global land use policy because it switches land from producing food to producing fuel. Burning ethanol or biodiesel releases the same carbon from exhaust pipes as burning gasoline and diesel. But the lifecycle analyses used by governments and researchers can claim that they reduce greenhouse gas emissions because they do not count this biomass-based carbon on the theory that it is offset by the carbon absorbed into the growing crops. In effect, the claim is that growing and burning biofuels does not add carbon to the air. Yet this benefit comes with the cost of not using land for other climate-beneficial purposes, such as directly storing carbon in forests or producing food so other land can remain forests. The ultimate climate question for biofuels is whether, and if so, by how much, the climate benefit of using land for biofuels exceeds the climate costs of not using land some other way.

By ignoring the carbon released by burning biomass, lifecycle calculations implicitly treat the devotion of cropland to biofuels as climate-free, i.e., as having no climate cost. If this land use cost is accounted for by governments at all, they use an economic model such as GTAP to estimate the carbon released by clearing other land to replace the food, known as indirect land use change or “ILUC.”

To determine a useful biophysical benchmark for ILUC, we can ask what the ILUC would be if crops were replaced by expanding cropland at average yields and on the average type of land producing each specific crop, such as corn or soybeans. This is the same biophysical approach governments and others generally take for other inputs in lifecycle analyses, such as fertilizer or factories. For example, to assign emissions to a car, the assumption is that one additional car is produced, and these emissions include a proportionate share of the emissions of building a car factory. Just as producing a car requires making a car factory, producing a crop requires making cropland, releasing carbon from trees or other native vegetation and soils. This approach assigns a proportionate share of emissions from producing cropland to each ton of crops. (Following both U.S. national and California policy, this carbon loss can be assigned per megajoule of biofuel assuming biofuels are produced on that land for 30 years while fully crediting co-products and by-products.)

As shown in Table 1, this theoretical ILUC is 200 gCO_2/MJ for corn ethanol and 330 gCO_2/MJ for biodiesel. These numbers, which exclude the production emissions from the use of fertilizer and fossil fuels, are roughly 3-4.5 times the direct reduction in exhaust pipe emissions by avoiding gasoline or diesel. This benchmark means that the GTAP ILUC estimate used by CARB is only around 10% of the average emissions of generating cropland to produce corn and soybeans. In the version of GTAP used in the GREET model developed by the Argonne National Laboratory, it is 5%.

GTAP’s 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 3 tonnes of carbon per hectare per year) (See Table 1). The GTAP versions in effect claim that all the cropland in Iowa – roughly the area devoted to U.S. ethanol production after accounting for by-products -- can be diverted to biofuel production or to any other use with minimal effect on global land use and minimal climate consequences.

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

	Average global carbon loss to produce crop	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					74
Corn ethanol	200	83	22	7.8 – 14.3	
Soybean biodiesel	330	179	27	9.1 – 12.1	

Biofuel figures are “land use cost” figures measured by the different methods, amortized over 30 years of biofuel production, while 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.

The GTAP estimates are also far below those 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. These high domestic emissions are particularly significant because international responses are likely to be higher, given that there is far more land abroad to convert. In Merfort et al. (2023), the authors estimated an ILUC of 92 grams CO_2/MJ for ethanol from high-yielding energy crops.

Economic Evidence Linking Biofuels to Deforestation

The empirical economic evidence provides no reason to believe that ILUC will be substantially less than the biophysical benchmark emissions. In fact, there is a strong body of empirical evidence that biofuels lead to deforestation and other agricultural expansion, with three steps in the economic chain of causation.

First, following basic principles of supply and demand, of which there is no economic disagreement, increased biofuel demand leads to higher crop prices. If it did not, no additional crops would be produced. Indeed, this is much of the purpose of biofuel policy.

Second, the prices of agricultural commodities around the world closely track each other. Even a cursory observation of commodity prices illustrates this. For example, a chart compiled by Reuters shows occasional short-term deviations but overall close tracking of changes in the prices of soybean oil in the U.S. and palm oil in Malaysia. Appendix F illustrates this, along with additional figures that show the tight relationship between world prices for several agricultural commodities and regions.

Rigorous econometric studies have shown that supply or demand shocks that change prices in one region simultaneously do so in others. For example, Roberts and Schlenker (2013) find that shocks to the agricultural supply of all the major grains and soybeans translate into similar price changes for crops around the world. As these authors note, large international conglomerates arbitrage international price differentials for grains and soybeans, so the causal mechanism is clear. Fackler and Tastan (2008) similarly show the closely arbitraged relationship between soybean prices in the U.S., Brazil, and Europe. These arbitraged relationships mean that increases in demand for biofuels in one region will cause similar price increases in different parts of the world, thereby stimulating cropland expansion wherever it is cheapest to do so.

Third, there is good evidence that increased crop prices lead to tropical deforestation. One set of studies at both global and local levels has shown strong correlations, although without using econometric techniques to prove causation (Berman et al. 2023) (Gaveau et al. 2022) (Cisneros, Kis-Katos, and Nuryartono 2021). But robust econometric studies using appropriate causal inference techniques have also found this effect. For example, Souza-Rodriguez (2019) found that agricultural expansion in the Amazon is highly responsive to agricultural returns, including returns for beef (Souza-Rodrigues 2019). Similarly, Sant'Anna (2024) found that sugarcane area has responded heavily to profitability, with a land area price elasticity of 3.89. This means that a 10% increase in the returns to sugarcane will, in the long run, increase Brazilian land used for sugar by 38%. Significantly, both of these econometrically rigorous papers find that long-run effects on land use are much larger than short-run effects. In the Amazon, this occurs in part because road networks expand in response to higher prices, which then encourages further clearing.

Although the long-established trend of yield growth currently meets most rising food demand, there is little evidence that increased demand, whether caused by biofuels or any other force, will result in higher rates of yield growth. The mere fact that global yields have increased massively over the decades even as prices declined suggests that factors other than rising prices are the primary drivers of overall productivity gains (Searchinger et al. 2015). Berry (2011) notes that the traditional literature in agricultural economics found little evidence that yields respond to prices. Berry and Schlenker (2011) show that the yields for U.S. corn follow almost a straight trend line, and they demonstrate that short-term deviations from trend can be overwhelmingly explained by weather fluctuations.

In the tropics, Souza-Rodriguez (2019) found no response of yields to prices for agricultural production in the Amazon, while Sant'Anna (2024) found a sugarcane yield-price elasticity that is only about 10% of the area elasticity. This implies that increased sugarcane ethanol supply comes from about 90% land expansion and about 10% yield increases.

Even short-run estimates focused only on the U.S. have found land expansion accounts for two-thirds of the U.S. corn supply response and all the soybean response (Miao et al. 2016); over the long run, the ratio of land responses should be higher even for corn because there is a time lag to converting cropland. At a minimum, the evidence indicates that any effects of higher prices on yields are a small component of overall yield gains.

The low (or zero) yield-price elasticities found in the literature may reflect a balance in which increased yields on already existing agricultural land are offset by the frequently lower yields of newly cleared land. It is sometimes argued that "basic economics" implies to the contrary, that increased prices will lead to increased yields. This will supposedly occur both through increased short-run use of inputs like fertilizer and in the long run through complementary investments like irrigation and increased innovation aimed at increasing yields. However, these economic intuitions only hold if the quantity of land is held fixed. Once area is allowed to adjust, economic theory makes no prediction as to what would happen, for example, to the ratio of fertilizer to land. Indeed, the simplest standard functional forms for production assume that this ratio will remain fixed.

Even if increased demand leads to increased R&D and infrastructure spending, their effects on global yields are ambiguous because they can lead to a shift in where agriculture occurs. As noted, the empirical literature on tropical agriculture documents a complementary investment in roads that favors land expansion over yield gains (Souza-Rodriquez 2019). R&D spending also enabled the competitive production of soybeans in Brazil, which probably saved land elsewhere but spurred expansion in carbon-rich lands in Brazil (Alves, et al, 2003) (DePaula 2023). Overall, both econometrically rigorous studies and simpler correlation studies support the conclusion that increased demand for crops anywhere will transmit globally and have a dominant effect of leading to cropland expansion in the parts of the world where cropland is expanding, particularly the tropics.

Reasons a Model Can Project Low ILUC

Land use models that project substantially lower ILUC emissions than the biophysical benchmark can rationally do so only because of one or a combination of three predicted economic responses. All significantly contribute to GTAP's low ILUC estimates:

- *Food reduction*: 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. (T.D. Searchinger et al. 2015; Hertel et al. 2010).

- *Intensification*: 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 assumes 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).

- *Low carbon conversion, including little forest loss*: 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 increases soil carbon.

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

The ILUC calculation should depend, in essence, on the ratio of the three different responses to increased prices: agricultural land expansion, intensification, and food demand reductions. This means that an error in one estimate will cause errors in others. All three responses must be soundly estimated across all regions to produce a scientifically useful ILUC estimate.

ILUC can also be lower just because strange things happen in a happen that cause ILUC to shrink for no biophysical reasons. This also plays an important role in GTAP.

Specific Recent GTAP Modifications that Lead to 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 since 2010. These decisions were critiqued in Malins, Plevin, and Edwards (2020) and responded to in Taheripour, Mueller, and Kwon (2021). These additional 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 existing 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 from 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 first discuss the issues raised by these recent changes because they help illustrate how a model can generate low ILUC estimates. We agree with the critiques in Malins et al. and 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 an increase 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, or if it contributes at all, by how much.

Highlighting the flaw in this analysis is the conflict between the assumption that 80% of U.S. cropping will be provided by increases in cropping intensity and 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 and 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.[3] 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 empirical "method" here is to assume that a short-run observed changes in double cropping reflects a large, long-run causal effect of crop prices 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. However, 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 more broadly below how these kinds of ad hoc adjustments turn modeling into mathematical forms of storytelling.

2. Demand-induced yield gains of cropland and pasture

The GTAP modelers have also 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, as a whole, found no yield intensification effect after the 1960's (Berry 2011). In fact, as discussed in Malins et al. (2020) and Berry and Schlenker (2011), corn yields in the U.S. follow an intensely linear trend independent of price. Furthermore, even if the yield intensification for corn were valid, applying that effect to other crops and to other regions lacks any foundation. The physical and economic factors that determine the ratio between land expansion and intensification will vary greatly both by country and crop.

In further revisions to the model, as discussed in Malins et al (2020), a large intensification effect has also been applied to pasture. As a result, when cropland expands into pasture, little pasture

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[3] USDA data available at Major Land Uses (ERS). For the remainder of the world, poor data makes it impossible to determine even what the true trends really are. 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.

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.'"

This is a particularly significant, pure assumption. The expansion of pasture into forest is, by a large factor, the main direct source of global deforestation (Weisse and Goldman 2021). Although lacking economic rigor, several papers have found statistical associations in Brazil between the conversion of pasture to cropland and the knock-on expansion of pasture into forest (Lapola et al. 2010; 2013) (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). This implies a significant knock-on effect if pastures are converted to cropland elsewhere. Other unjustified model features, discussed below, lead GTAP to project that cropland will mainly expand into pasture. The combination means that this pure assumption of a large intensification response assumes away most ILUC.

3. Cropland pasture

The introduction of a category of land called cropland pasture leads GTAP 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. 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 causes 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 on real changes, as USDA has cautioned. Malins et al. also observe that the GTAP authors employed no economic estimates to differentiate changes in cropland pasture due to biofuels from trend line changes. They also note that there is no international category of cropland pasture.[4] We agree with these critiques and add two observations.

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[4] 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."

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 et al. 2021). Even if this were true, in Brazil this category of land use has not only not decreased during the rise of biofuels but increased by 20% from the average of 2003-05 to the average of 2019-2021.

Second, the claim that converting cropland pasture to cropland increases soil carbon is not only empirically contrary to virtually all evidence (Conant et. al. 2017) but also conceptually flawed because it fails 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. However, due to fluctuations in price, there will always be “frictional” cropland, i.e., land that is cropped in some years and not in 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 parameters and economic structure of the GTAP model in general. We find that these lack an economic foundation.

1. Basic Structure of GTAP

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 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 extent) other crops or foods replace those losses. (These are known as “cross-price” effects, often expressed as “cross-price elasticities.”) Price changes can affect consumption and production in numerous ways. For instance, 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 switch to other foods. They may also potentially reduce their overall food consumption, in turn buying more non-food 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 overall energy consumption 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 highly disaggregated ways: by country or groups of countries, by multiple agroecological zones (AEZs) within countries, and by product. It projects to do so not just in agriculture but throughout the economy.

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 for the use of cropland. This nest, in aggregate, generates a total cropland area. This area is included in a higher-level nest, in which the use of land for cropland competes with the use of land as pasture for livestock and as 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, will increase or decrease as a result of changes in price. We call this the "nest parameter."[5] However, this nest 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 of the total revenue of all products, or the share of all input costs, within that nest.[6] For example, the elasticity of cropland area within each agroecological zone depends on both the nest parameter and on the share of total rent cropland provides of the rent of all land uses in that agroecological zone, including the rents of pasture and wood-producing land. 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.[7]

As we discuss now below, this formula is chosen for its computational tractability, not for its empirical reality. As explained below, this formula even contradicts the highly limited economic evidence cited by the modelers to justify their choice of nest parameters because, to our knowledge, none of these studies found that the ultimate elasticities depended on the

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[5] 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.

[6] 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.

[7] 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.

expenditure share within a nest. This model structure is understandable as an academic research strategy, but it lacks empirical credibility for use 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.[8] Yet GTAP only claims to base a handful of these parameters directly on any empirical economic analysis. This means that except for a very few of products and regions, there is no cited underlying supply or demand study for the product anywhere let alone a product in that region. Although some reference may be made for a nest parameter, this parameter is almost always based on analysis of a different product or of the product in a particular location if it is based on any study at all. GTAP's general approach is to apply the same parameters to quite different products or inputs and in multiple or all regions, although there is no sound economic reason to believe they are the same.[9] As illustrated in Appendix B, for large categories of activities, the parameters are set by pure assumption to a fixed fraction of some other set of parameters. [10]

Even for the parameters that are claimed to have an empirical basis, none appear to be derived using modern econometrics. There is a 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.[11] 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-to-few of the thousands of parameters in GTAP is based on a high-quality application of consensus econometrics.

Remarkably, for large parts of the model, the parameters governing elasticities of demand are the same as those governing elasticities of supply. This is remarkable because a major focus of economics is typically to determine the differences between the two. (The differences determine changes in social welfare costs and benefits, and who bears or receives them.) For ILUC, the difference between supply and demand responses plays a large role: To the extent that the economic response to diverting crops is to reduce consumption, there is no ILUC. However, there is no reason to believe supply and demand elasticities are the same. This assumption alone makes it challenging to treat the ultimate model results seriously.

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[8] As of August 2024, the latest GTAP model contains 94,248 non-zero parameters, while GTAP-BIO includes 6,800 parameters, of which 4,673 have non-zero values.

[9] For example, 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.

[10] 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.

[11] The parameters in the CGE models are mostly based on approximations and are typically neither estimated simultaneously nor with instruments (Yang and Preckel 2024).

The factors that govern land use change (the land use nest parameters) illustrate the problems that occur even when the model has identified some source for some parameter in one location. 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.*[12] It focused exclusively on land use changes in the United States. Using 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 in the U.S. Despite these differences, 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 et al. 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. It will also depend on economic factors, including 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. Given both the vast physical and economic differences around the world and given how much variation there was in the U.S. alone, it would be an extraordinary coincidence if this U.S.-derived average 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 country or region. Instead, they still used the U.S. parameter as a kind of global middle benchmark, although it was not. Then, after surveying regions with different recent cropland expansions, the authors subjectively raised or lowered their nest parameter from this benchmark in different regions. They did so without using any standard econometric method. In other words, they made no effort to determine if observed land transitions were caused by price changes as opposed to changes

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[12] 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). Ahmed, Hertel, and Lubowski (2009) is the paper that translates the Lubowski estimate into the CES form utilized in GTAP as referenced in the supplement to Hertel et al. (2010).

in any other determinants of demand and supply. In fact, 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*. This has an extraordinary implication. Although this U.S.-derived parameter for the U.S. remains the *only* land use change parameter in the world for which the GTAP authors claim to have *any* econometric support, they picked a new U.S. value that greatly contradicts it.

Model parameters matter. The GTAP model choices and uses of parameters lack empirical support in multiple ways: (1) GTAP lacks any underlying economic study for the vast majority of parameters; (2) it misapplies the few estimated parameters to other regions and products; (3) it commonly assumes that supply and demand elasticities are the same; (4) in recent versions, it makes further ad hoc adjustments to the land area elasticities that even contradict the sole reference cited. Any one of these limitations disqualifies GTAP as a potentially valid predictor of economic effects.

3. The role of expenditure shares, which leads to misapplication of these parameters and determines critical substitution patterns without any economic basis at all

There is also a fifth fundamental empirical flaw.

Even if some or all the parameters used in the model had some empirical basis, GTAP misuses them to project wildly different supply and demand relationships. This is because, as discussed, nearly all the demand and supply elasticities in GTAP are determined not just by one "nest parameters," but also by the share of expenditures each product or input has within each "nest." (Depending on the nest, this expenditure share can be a share of costs or a share of revenues.) This feature was selected because this type of data is relatively easily available. But the use of the expenditure share formula to determine elasticities has large consequences, lacks an empirical basis, and contradicts the limited economic studies cited by the modelers.

A cake recipe helps illustrate both how an expenditure share formula works and why it cannot, in general, be used to replace empirical estimates of how demand or supply of 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 substitute for others if the others increase in price. However, that will depend not only on the price of each ingredient but also 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 to make a cake rise, it is unlikely that increasing its cost would cause bakers to use less baker powder per cake baked. That is particularly true given the modest contribution to the total costs of a cake of a tablespoon or two of baking powder. With a high enough price increase, it is conceivable that a baker might substitute more egg whites 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 the determinative factor in 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 ingredient will help determine how much its use rises or falls. In addition, the percentage of expenditures will solely control what is substituted. For example, 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. The ratios of quantities of the other ingredients replacing baking powder (known as the diversion ratios) 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 expenditure shares, even though their functional roles are distinct from baking powder.[13]

Cakes are not specifically in GTAP, but this expenditure share function is key to determining the elasticity of demand or supply for all products and inputs in GTAP. For example, if the demand for cropland—and therefore its price—increases, the quantity of cropland expansion in each of the many "agroecological zones" will depend on a nest parameter, but also on the cropland's share of the total revenue from rents in that zone. This choice of elasticity lacks an empirical basis. Moreover, the amount of land that comes from pasture or wood-producing land will depend entirely on their own revenue shares.[14] It also lacks an empirical basis.

In fact, this means that the ultimate choice of elasticities contradicts the few references cited for elasticities. For example, the model's choice of land elasticity was originally based on *Lubowski*. But *Lubowski* found that elasticities vary with soil and prior land use, not with land revenue shares within an agroecological zone. If *Lubowski*'s elasticity is valid, then GTAP's changing of it into another elasticity based on expenditure shares must be wrong.

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

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[13] A 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 expenditure diversion ratios do not depend at all on any parameter, but only on revenue/expenditure shares.

[14] For simplicity, we explain this as a change in the quantities of land. For reasons discussed below, the actual changes are in the quantity of revenues from each land use, which leads to physically impossible results – an additional problem.

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 different treatments based on their heights.

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 expenditure share. This is not only true for shifts among land but also for nearly all other statistical relationships in the model.

This expenditure structure also means that many critical substitution patterns, so-called diversion ratios, lack any connection to an economically illustrated estimate. For example, if demand for crops increases and cropland expands, the land must come either from pasture or forest. However, the amount that comes from one versus another, known as the diversion ratio, is a fundamental focus of the model and critical for ILUC. In GTAP, how the new land comes from forest versus pasture depends entirely on the rental revenue shares of land uses in each agroecological zone. No economically estimated parameter has any role in setting this diversion ratio.

This structure can also lead to perverse results. For example, as modeled, the ethanol mandate leads to a large price increase for gasoline, producing a decline in the aggregate consumption of gas 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 because price declines should lead to increased consumption. As explained in Appendix E, these results, which contradict economic sense and do not seem to have 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 expenditure share structure is probably influenced by an intuition that for some products, the amount people spend on close substitutes is a guide to what they might purchase if the first product increases in price. For example, suppose people in a country buy a certain amount of pork, chicken, and dairy, and the price of chicken goes up. In that case, there is an intuitive assumption that the relative switch to pork or dairy might in some way reflect the relative shares of each protein consumed. But an intuition is not evidence. And even the direction of the intuition is not clear. If chicken prices rise, would a large dairy consumer be more likely to switch from chicken to dairy on the theory that he likes dairy or more likely to switch to pork on the theory that he already eats enough dairy? The GTAP model assumes the former, but it could be the latter. And there are many contexts in which any relation to expenditure shares makes little sense. A cake recipe is one. Land use is another because the different physical characteristics of each piece of land will have prominent effects on their uses.

The lack of empirical basis for the critical role played by expenditure shares makes GTAP's use for policy not credible.

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

Because of the fundamental limitations described above, GTAP cannot credibly estimate ILUC or, to the extent we can tell, any other economic prediction, regardless of the result. In addition, both this flawed structure and numerous additional structural or parameter decisions that lack empirical foundations explain what leads GTAP to project low ILUC.

1. GTAP economic functions create physically impossible land use results and require artificial adjustment that greatly reduces ILUC

Because land area is fixed, a land use model needs to be able to determine how much cropland expands and how much of this new cropland area comes from each alternative land use, such as pasture or forest. GTAP, however, does not actually base its economic function for allocating land on physical land areas. As a result, its economic features 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 the share of their combined rents within an agroecological zone. When there is a shock to the system, such as more demand for cropland for biofuels, it is not the physical areas in changes that must match. Instead, in the first-order calculation, the increase in revenue from cropland needs to be matched by a decline in revenue from pasture and forest. Because each acre has a different rent, matching the revenues leads to a mismatch of physical areas. Depending on the different price changes and other characteristics in different agroecological zones, the model "creates" physical land or "destroys" it.

This feature results in vast discrepancies. In the United States, the decreases in forest and pasture from the model runs for California are roughly ten times larger than the projected increases in cropland area (Appendix A). For an economic model of land use change, this is not a minor challenge. The model's economic theory states that substitutions depend on shares of each land use in the total rent. If the resulting model claims that land is created or destroyed, it means that the economics are fundamentally incorrect.

GTAP compounds this error in the way it then responds. To deal with this problem of fictionally created or destroyed land, GTAP modelers have added a pure adjustment factor, which automatically reduces or increases the area of pasture and forest to match the real physical area. Such an arbitrary adjustment does not make the model economically valid. For example, if a model of the economic benefits of increased education were to claim that individual incomes increased in total vastly more than the total national income increased, it would not be a sign of a valid model that the model then reduced individual incomes proportionately to match the national income.

In addition, the adjustment factor applied by GTAP generates results that are inconsistent with its economic projection even of the percentage of land conversion that results from forest and pasture. This results in a further lower ILUC. In Appendix C, 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 model's economic projections for the U.S. total 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 that this share shrinks to 34% after the adjustment. In other words, the adjustment reduces not only the total ILUC area but also reduces the relative contribution of forests to supplying new cropland.
- The economics in GTAP predict a decline in forest area in several agroecological zones, including AEZ7. However, after the adjustment, the model predicts an increase in forest area.

To summarize, the model's economic structure produces physically impossible results. The imposed adjustment factor then further generates an inconsistent result and greatly lowers the ILUC.

2. GTAP cannot allow conversion of unmanaged land, and thereby forces intensification and decrease in food consumption rather than agricultural land expansion.

Previous commentary on GTAP has noted that it cannot model and does not allow conversion of unmanaged land. Unmanaged land, such as wild, publicly owned forest, is land that does not have a rent, i.e., does not have an economic return. GTAP cannot model it because it assumes that every economic interaction is based on an input's economic return.

Unmanaged land can be a large part of a country's land, and its conversion is a major focus of global agricultural land expansion. Making unmanaged land 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).

However, this flaw in GTAP will depress ILUC even more than estimated in Plevin et al. (2022) because the lack of unmanaged land also leads to more limited conversion of managed forest and pasture. In GTAP, grasslands and managed forest exist not as physical entities but only as land that supplies livestock or wood products. Yet under GTAP, if increased crop prices encourage cropland conversion of these lands, livestock products and wood products cannot be alternatively supplied by expansion into unmanaged land. The rental value of pasture and managed forests therefore increases more, and this causes the model to resist their conversion, which further decreases ILUC. In effect, because the model does not allow people to bring more unmanaged land into human use, the model will structurally favor cropland responses that do not cause ILUC even of managed land.[15]

3. The expenditure share formula conflicts with the sole economic source of the key land use parameter and requires parameter choices that reduce conversion of forest and conflict.

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 the conversion of forest to pasture than increases in the profitability of forest had on the 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 D.) The reason is intuitive. Wood production and therefore forest “rents” are much lower than cropland rents (Lubowski 2002). It therefore 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 much higher elasticities for cropland expansion than forest expansion.

But GTAP requires that the same nest parameter, which determines the elasticity, be used for both cropland and forest. To provide this single parameter, the GTAP authors chose a parameter that averages the elasticities of the different land uses. (Appendix D provides a more specific description.) As a result, GTAP *deliberately* chose a parameter that overstates multifold the conversion of cropland to forestry in response to an increase in forest profitability. This means that relative to the findings of *Lubowski*, if crop prices increase, GTAP will overestimate the pushback effect of forests against conversion.

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

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[15] 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,” i.e., managed forests, 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 even reduces ILUC emissions.

4. Additional, incorrect assumptions about managed forests work together with the expenditure-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 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). Managed forests therefore can supply more wood – with a carbon cost not counted in GTAP – to replace any wood supply lost by conversion of some managed forests to cropland. It is therefore not necessary, as assumed in GTAP, to convert agricultural land to forest somewhere to supply adequate wood to meet demand.

These limitations of the GTAP structure work together not only to resist forest conversion but also to cause 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). This feature too lowers ILUC.

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

GTAP builds into the model factors that greatly constrain trade, which are known as Armington elasticities. The lower the Armington elasticity, the more restricted the trade.

This form of model is based on an old idea that trade patterns in manufactured goods can best be explained by a "home bias" for domestic products. This constraint seeks to account for such phenomena as a preference in France for cars from Renault and in Germany for cars from Volkswagen. In reality, this "home bias" reflects the fact that products, such as cars, are not homogenous. But some products are homogeneous, such as soybeans and corn, which means the will be traded more freely. Yet strangely, the GTAP model assumes that the home bias for homogenous agricultural commodities like soybeans and corn is not only as great as manufactured goods but greater. For a point of reference, oil is considered highly tradeable globally and has an Armington parameter of 5.2, and the GTAP model typically uses an average of 3 for manufactured goods, while for basic crops such as coarse grains, the model assigns a parameter of 1.3. This choice of parameter implies that consumers care more about essentially indistinguishable features in animal feeds than they care about differences in cars or watches.

This feature of the model can result in large differences in the prices of crops in different regions that do not occur. For example, the 2010 version of GTAP estimates that the ethanol shock analyzed for California results in a 16% rise in the price of corn in the U.S. but only a 1% rise in the EU. As explained more thoroughly in Appendix F, this structure and assumption contradict 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. As found by Roberts & Schlenker (2013) and as illustrated in Appendix F, prices in different world locations are closely linked. The GTAP predictions are also contradicted by the fact that the growth of biomass-based diesel in the U.S. is closely correlated with increases in imports of vegetable oil to the U.S. (Malins and Sandford 2022).

The empirically contradicted GTAP trade model thus forces much of the adjustment to U.S. biofuel policy to remain in the U.S. This then forces much of the equilibrium adjustment onto predicted U.S. consumption and U.S. livestock intensification and limits the model's prediction of agricultural expansion in developing countries, which is where most agricultural expansion occurs. A realistic model of world trade would predict that much more of the adjustment would occur outside of the US, particularly along active forest/crop boundaries, as in the well-measured empirical papers cited in the introduction.

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.

Total Effect of GTAP Problems

Many of the unjustified effects that we have discussed work together to generate an extremely low ILUC:

- Several effects we have described cause the economic component of the model to select conversion of grassland rather than forest.
- The assumption of large-scale pasture intensification in response to demand further avoids the pressure to clear forests to replace pasture converted to cropland.
- The ad hoc physical land adjustment further reduces the role of forest conversion relative to grassland.
- After all these factors combine to limit forest conversion, the claim that much of the grassland conversion to cropland increases soil carbon further lowers ILUC.
- Although the compound effect is to ensure the low conversion of forest and the low ILUC, the assumption that the great majority of additional cropland results from growing crops more frequently on existing cropland lowers ILUC even more.

These multiple unjustified effects also mean that sensitivity analyses that adjust parameters have little meaning. If a parameter change reduces the effect of any one factor, many other unjustified factors remain to ensure a low ILUC.

Alternatives: Carbon Opportunity Costs

Given that GTAP is unreliable for the purpose of measuring ILUC, a sensible regulatory alternative is to measure the climate cost of using land for biofuels using the same basis approach that lifecycle analyses typically use to estimate the emissions of any other fixed input, such as a car factory. Making a car requires making a car factory, and the emissions from constructing the factory are typically allocated to the use of the car. For crops, the factory is the cropland, and its major emissions are the carbon lost by converting forests and savannas. Although a factory, like cropland, already exists by the time a car is made, the reasonable assumption is that an additional car will ultimately require a little bit more of a new factory, so some small part of the costs of a car factory must be assigned to each car. Similarly, in a world that is expanding cropland, each hectare used requires another hectare, so some of its emissions need to be assigned to each ton of crops. The carbon cost of devoting land to biofuels would then be this lost carbon sequestration.

This straightforward approach, which has come to be known as the “carbon opportunity cost of land” (Timothy D. Searchinger et al. 2018) (Hayek et al. 2021), generates the “benchmark” ILUC costs shown in Table 1. One argument about this approach is that it (in practice) uses the average carbon opportunity cost of land rather than the opportunity cost of marginal land. However, Table 1 demonstrates that the marginal carbon cost of land would have to be wildly lower than the average cost just for the greenhouse gas emissions of biofuels to equal those of fossil fuels. We have discussed evidence that the marginal agricultural land in the world right now is tropical forest, so deviation of the required magnitude to find climate benefits from biofuels seems implausible.

There is also a methodological inconsistency between using a worldwide economic model to analyze the emissions from land use and the methods used to analyze those from gasoline, to which it is compared. For a gallon of gasoline, governments generally evaluate the emissions from producing and burning it. But if governments were to use an economic model to estimate the emissions savings of replacing gasoline with biofuels, they would likely estimate that others would use slightly more gasoline because of lower gasoline prices. As a result, the emissions “savings” from displacing gasoline with biofuels would be lower, substantially so under some estimates (Hill, Tajibaeva, and Polasky 2016). The use of reduced food consumption to lower emissions from biofuels but not from gasoline generates an inconsistent comparison.

Even more fundamentally, carbon opportunity costs are consistent with how economists generally understand the costs of anything. In economics, cost means opportunity cost. Even in theory, global economic models like GTAP seek to determine the climate effect of spending money and devoting land to biofuels versus the status quo. The real cost is the lost opportunity to use the same money and the same land in the best alternative way to save carbon.

The Carbon Opportunity Cost approach has the added value of not rewarding predicted decreases in food consumption. These reductions in consumption, according to GTAP and some other models (T.D. Searchinger et al. 2015), are not targeted at the overconsumption of land-intensive products by the wealthy, such as beef in the West, but result from general increases in prices and are normally viewed not as a benefit but as a social welfare cost. The costs are particularly high because the burden is likely to fall most on the global poor (Dorward 2012). (Green et al. 2013).

Another likely large carbon opportunity cost for biofuels is the loss of land that could be used for solar power. Finding appropriate sites for the vast solar power needs already presents challenges and will likely lead to emissions from land use change directly or indirectly (van de Ven et al. 2021). Yet, biofuels typically require at least 250 hectares of land to match the electric vehicle miles that can be driven using one hectare of solar panels (Searchinger, Beringer, and Strong 2017).

If governments wish to use other approaches, the question they should ask is whether the economic evidence supports claims that biofuels are likely to reduce greenhouse gas emissions. This would only be possible if the land use costs are a small fraction of the average carbon lost from generating cropland to produce crops (as shown in Table 1). As summarized in this paper, the economic evidence fails to support such a view. Based on this sounder analysis, governments can avoid encouraging biofuels simply by assigning them the same emissions as gasoline or diesel.

Models Without Firm Evidence

In Taheripour et. al. (2021), the GTAP modelers do not claim to have significant econometric support for the GTAP 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, including overfitting of models and running regressions repeatedly until some strong correlation with some variable shows up, known as P-hacking. Economics underwent a credibility revolution in which even proper statistical techniques were shown to generate improper elasticities because they did not use “instruments” to separate correlations from causal effects. The calibration exercises the GTAP modelers employ generally involve ad hoc adjustments to parameters that do not even rise to the level of “statistical errors” because they do not use statistics at all. These exercises, it appears, assume stories that the modelers believe can explain what is happening in the world. Parameters are then altered to generate the assumed stories. This is not credible because there are innumerable competing stories.

A common argument is that some comprehensive model is better than nothing, and the desire of policymakers to rely on some is understandable. But models that rely on unsupported assumptions are not better than nothing. That is true even if such models did not have the systematic biases shown here for GTAP. Such models cannot be properly used to justify any particular policy because it would always be possible to justify competing policies by making different assumptions to explain the same data.[16] Relying on such modeled stories also encourages policymakers to ignore the lessons of more focused, robust economic results, generating false confidence that we can overlook large risks.

Although valid economics can rarely provide the kind of all-encompassing and disaggregated predictions claimed by GTAP, that does not mean economics lacks an important role. In this paper, we have provided examples of rigorous studies that confirm the likelihood that increased prices lead to agricultural expansion and forest loss. Ultimately, sound policy should build on this type of evidence, even if it does not purport to generate precise ILUC numbers. For biofuels, the evidence strongly suggests that policymakers should not risk physically transforming much of the earth, with negative consequences for the climate.

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[16] An absurd model helps to illustrate this point. Imagine a model that claims that on a particular street, the number of pizzas eaten at each house is determined by the number of letters in the owner's last name plus the street number multiplied by a coefficient. Each coefficient is then selected to match the known number of pizzas eaten in that house. This model can be calibrated to fit the data perfectly. If we assume that household desires for pizza are similar year to year, this model will also likely do a reasonably good job of predicting pizza consumption the next year or the year after that. But because it is nonsense, it will do a terrible job of predicting the number of pizzas eaten if people with a different last name buy a house or houses are renumbered. Moreover, a model could have the same perfect fit for pizza consumption if coefficients were fit to the letters of the first name, or only to the last two digits of the house number, or to the number of magazine subscriptions in each household. That would be true even though each alternative model would make vastly different predictions about pizza consumption in the event of change.

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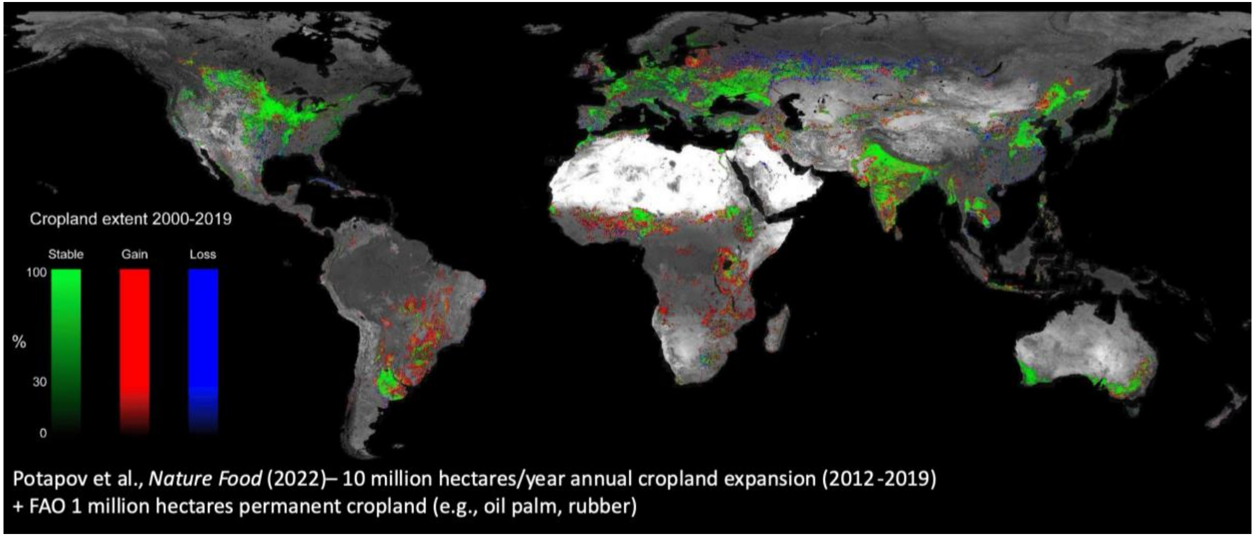
Appendix A: Selective graphics illustrating global land use change

Figure A1: Areas of expansion recent cropland change

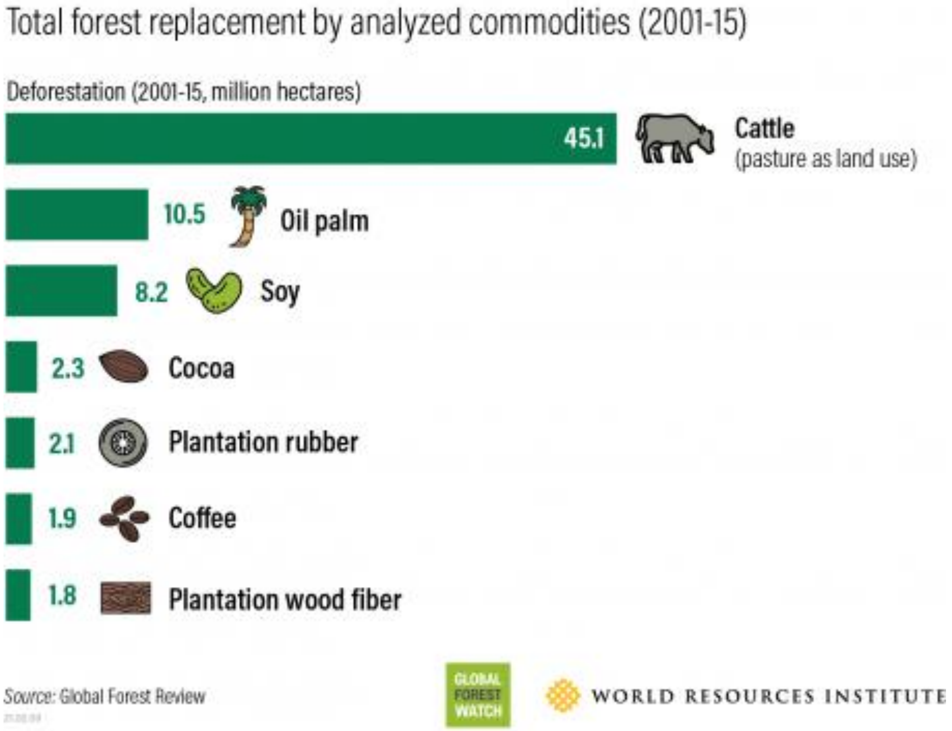


(Source: Matt Hanson)

Figure A2: Primary deforestation areas for oilseed crops

(Source: World Resources Institute)

Figure A3: Direct uses of recently deforested land



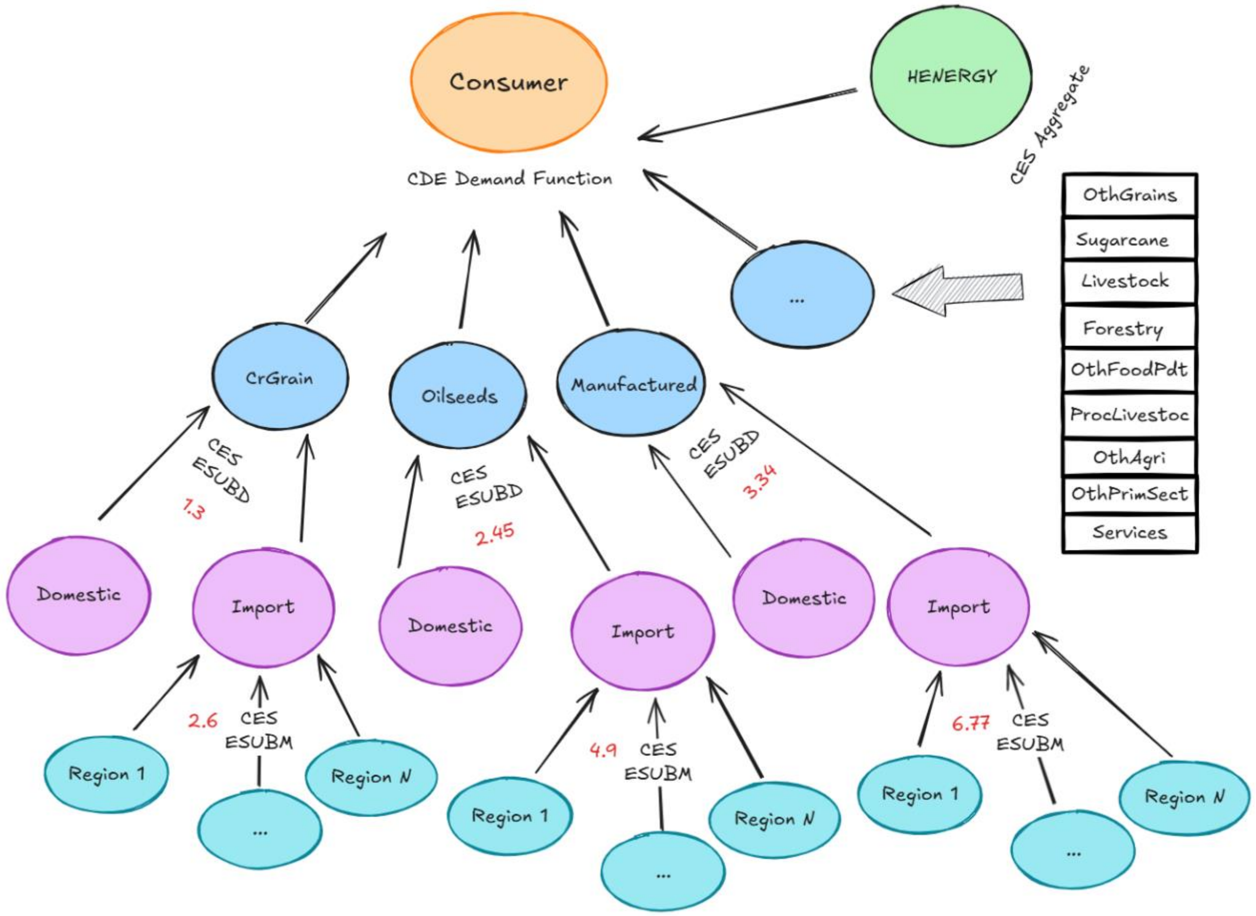
Total forest replacement by analyzed commodities (2001-15)

Source: Global Forest Review

Appendix B: Examples of CES Parameters Assumed as Percentages of Others

Figures B1 illustrates how GTAP often assumes that certain elasticity parameters, known as CES parameters, are just fractions of others. Figure B1 shows both the demand and supply elasticities, which are assumed to be the same, of consumer choices of major baskets of goods. The sources of these goods as coming from domestic supply or imports are then governed by a separate CES parameter. Some paper is occasionally cited for this parameter (although not necessarily a paper analyzing the same parameter nor a paper using proper econometric methods). However, imports could come from different regions. The CES parameters for these regions are simply assumed to be double those of the parameter that governs imports versus exports. This means that no actual economic analysis is used to estimate which region additional goods, including crops, will come from. That is true even though the claim to be able to project such sources of crops is a core reason claimed to use an economic model to estimate indirect land use change.

Figure B1: Nesting structure and parameters that govern imports



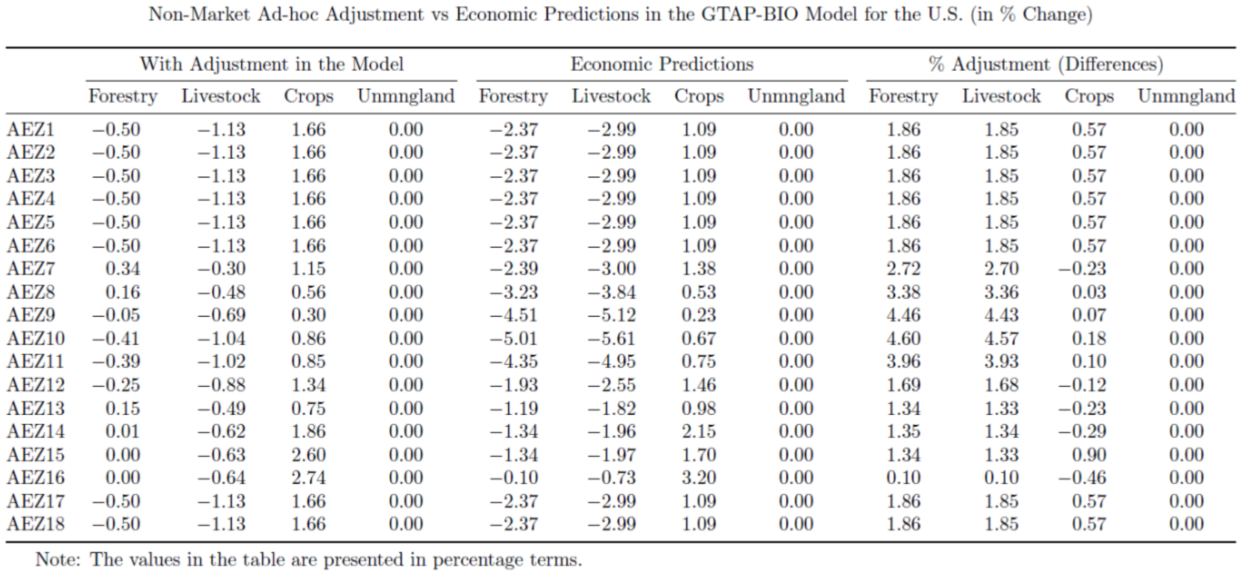
(Source: Authors' drawing based on the model structure of the GTAP-BIO Model)

Appendix C: 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 used by the California Air Resources Board. In Table A1, the columns are U.S. agroecological zones (AEZs), i.e., parts of the U.S. claimed to have similar growing characteristics. The columns labeled "With Adjustment …" are the reported land use changes. The three columns labeled "economic predictions" are the values projected by the economics and before 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 C1, we see that forestry and livestock land are arbitrarily reduced by the same number of percentage points. In several cells is the column for forestry areas "with adjustments," forestry area is supposed to expand even though the economic prediction is that it will contract. The table further shows how the model does not allow changes in unmanaged land.

Table C3 (on the next page) applies the GTAP land use changes in CO_2 emissions to the physical land use changes in Table C2. 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 C1: GTAP Economic Predictions of U.S. Land Use Change from Ethanol, Hand-of-God Adjustments and Adjusted Results (percentage changes)

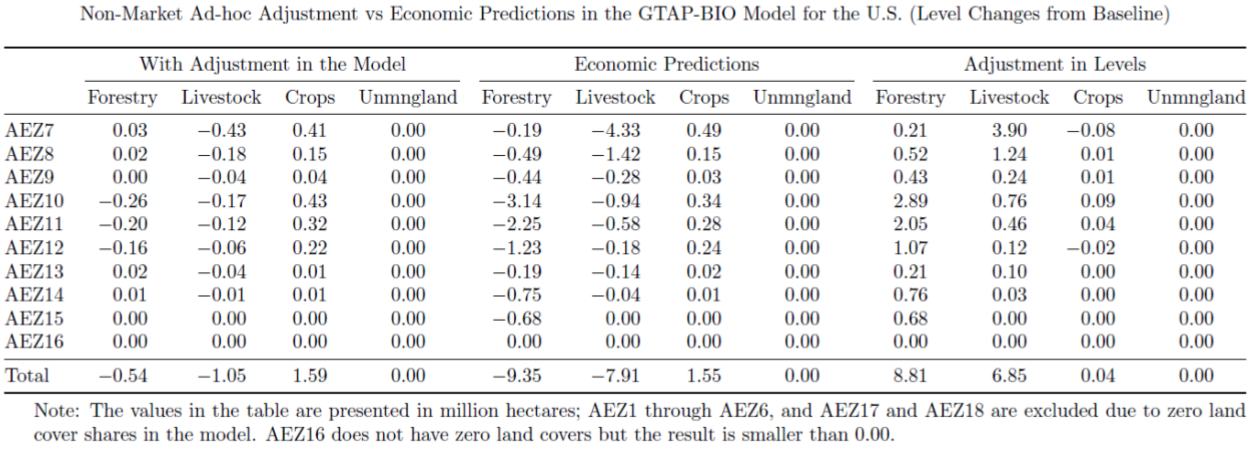


Non-Market Ad-hoc Adjustment vs Economic Predictions in the GTAP-BIO Model for the U.S. (in % Change)

	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 C2: GTAP Economic Predictions of U.S. Land Use Change from Ethanol, Hand-of-God Adjustments and Adjusted Results (hectares)

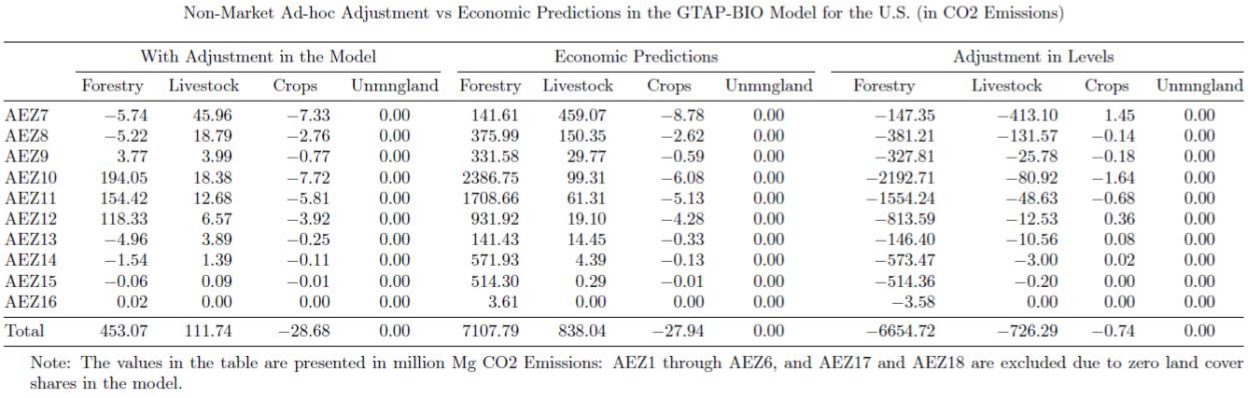


Non-Market Ad-hoc Adjustment vs Economic Predictions in the GTAP-BIO Model for the U.S. (Level Changes from Baseline)

	With Adjustment in the Model				Economic Predictions				Adjustment in Levels			
	Forestry	Livestock	Crops	Unmngland	Forestry	Livestock	Crops	Unmngland	Forestry	Livestock	Crops	Unmngland
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
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; AEZ1 through AEZ6, and AEZ17 and AEZ18 are excluded due to zero land cover shares in the model. AEZ16 does not have zero land covers but the result is smaller than 0.00.

Table C3: GTAP Economic Predictions of U.S. Land Use Change from Ethanol, Hand-of-God Adjustments and Adjusted Results (emissions)



Non-Market Ad-hoc Adjustment vs Economic Predictions in the GTAP-BIO Model for the U.S. (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
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
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: AEZ1 through AEZ6, and AEZ17 and AEZ18 are excluded due to zero land cover shares in the model.

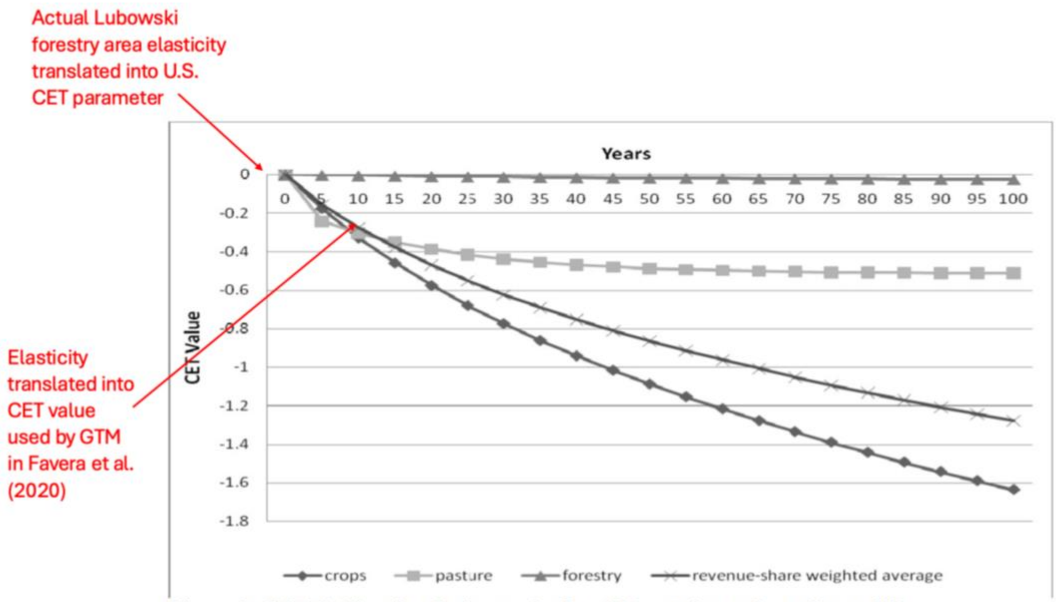
Appendix D: How GTAP Transforms *Lubowski* Land Use Transformation Elasticities to GTAP Parameters and the Resulting Inconsistencies

Figure D1 shows how GTAP translated the “own price” elasticities from *Lubowski* into the 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 D1 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. For GTAP, the modelers choose one 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 this 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 D1: How GTAP derived its transformation parameters from Lubowski (2002)



Actual Lubowski forestry area elasticity translated into U.S. CET parameter

Elasticity translated into CET value used by GTM in Favera et al. (2020)

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

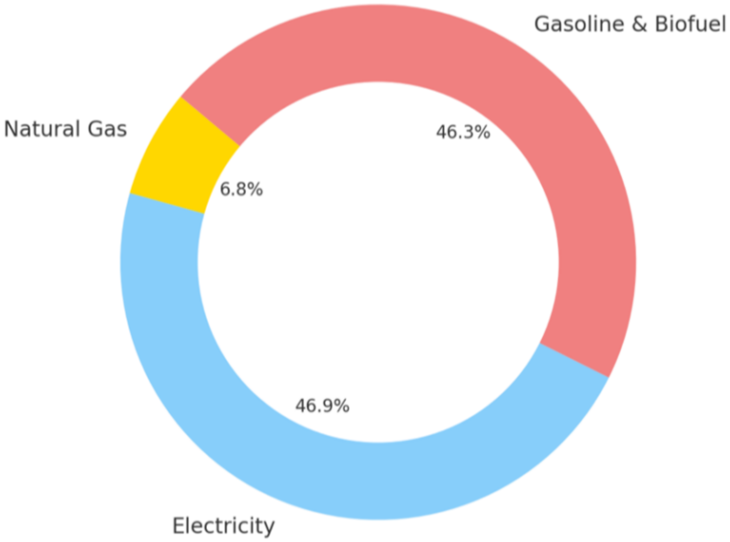
(Source: Ahmed et al [2008])

Appendix E: 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 illustrates 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 base year of the model.[17] "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 E1: Baseline consumption shares in the model, consumer energy consumption



1. Gasoline & Biofuel is a combination in the GTAP model consisting of petroleum, ethanol, and biodiesel for household consumption.
2. The combination of coal and oil consumption take less than 0.1% baseline data and are thus omitted here.
(Source: Authors' drawing based on the simulation)

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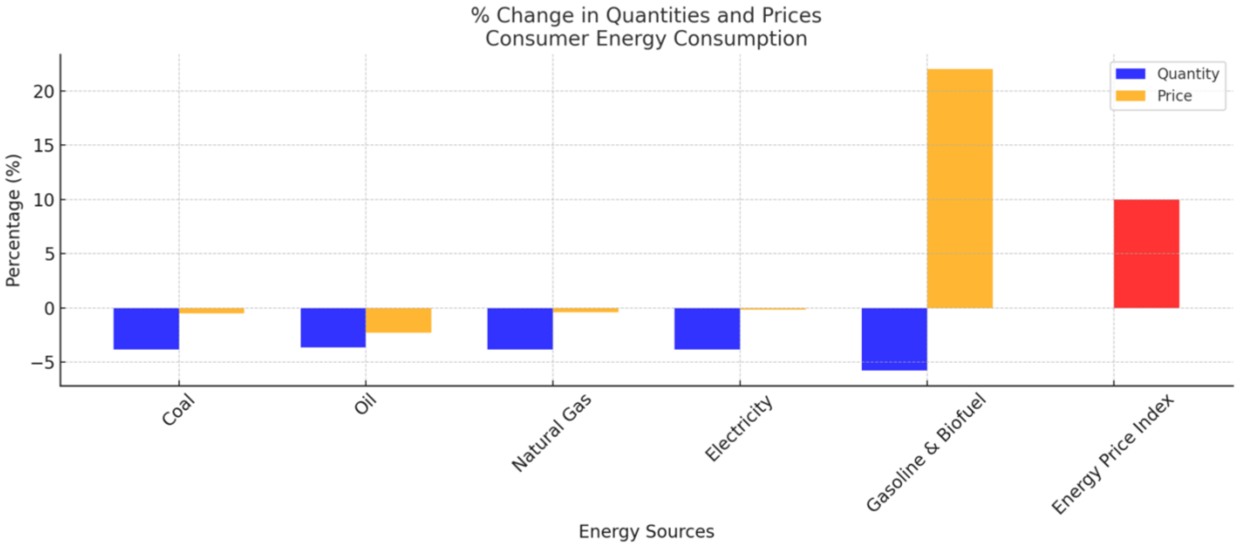
[17] We frequently rely on the 2010 version of GTAP-BIO because it is by far the best documented version of the model. We have verified that most key features remain in place in a later CARB version of the model, although some components of the overall model are further elaborated by CARB.

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

Figure E2: Percent change in quantities and prices, consumer energy consumption



Gasoline & Biofuel is a combination in the GTAP model consisting of petroleum, ethanol, and biodiesel for household consumption.
(Source: Authors' drawing based on the simulation)

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.[18] This is contrary to

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[18] 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.

reality, but the modelers can only do simple policy exercises. They require that 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 E2 shows 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 F: 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.[19] 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. Although some GTAP extensions, like GTAP-HET (i.e., GTAP-Melitz 2003), are available, the model still lacks distance effects and is not widely used for environmental policy analysis.

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. Their statistical tests confirm that "the United States/Brazil/Rotterdam markets appear to be fully integrated" in soybeans (Figure F2). In fact, even broadly reproduced business statistics show that prices even of different vegetable oils in different countries closely track each other (Figure F1).

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[19] Arkolakis, Costinot, and Rodríguez-Clare (2012) demonstrate a simple approach where counterfactual welfare changes can be derived using only two sufficient statistics, as opposed to requiring over 5000 lines of code, even in the standard GTAP model.

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.

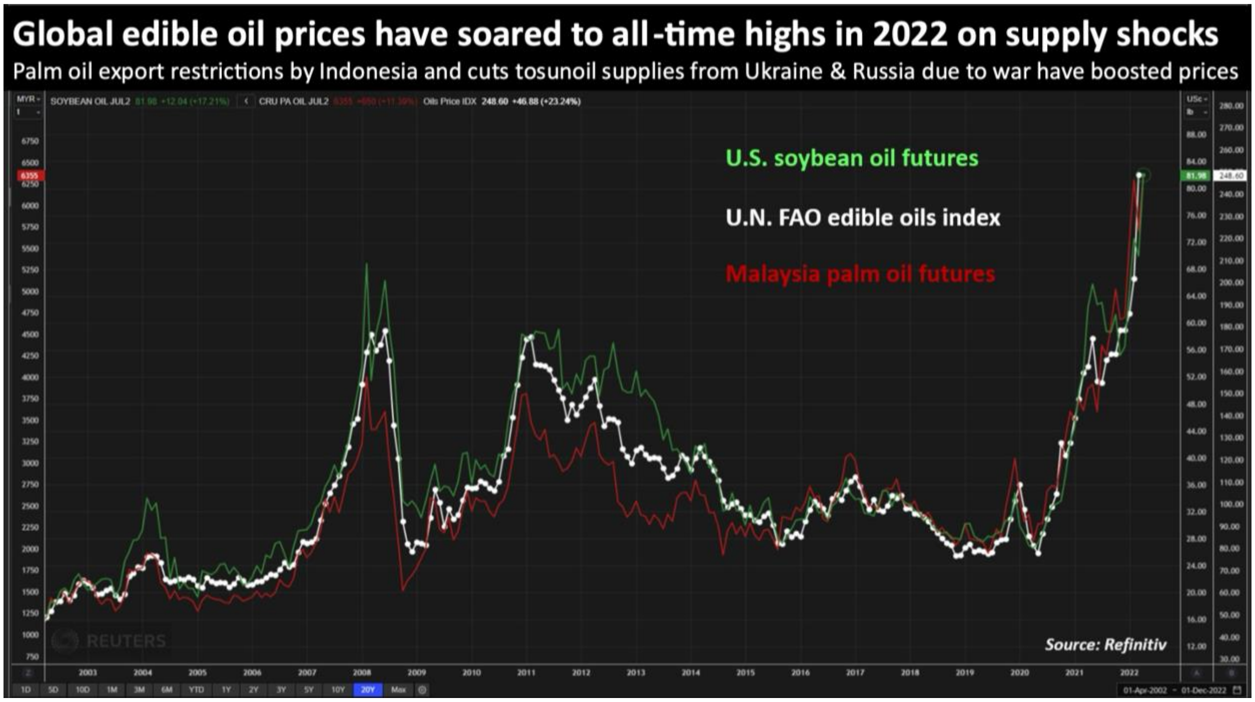
In (Villoria and Hertel 2011), the authors conceptually defend the GTAP trade model through analysis claiming that data does not prove an integrated world model of prices. Their analysis, which conflicts with papers cited above, is not convincing:

- 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); (Steve 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.

The GTAP model predictions also appear to contradict actual experience. Figure F5, taken from Malins & Sandford (2022) shows how increases in biomass-based diesel consumption in the U.S. have been almost perfectly correlated with increases in vegetable oil net imports. Figure F3 shows how maize prices closely track each other in different parts of the world. (Although the Ukraine war temporarily caused Ukrainian prices to briefly decline, even they quickly recovered to track those elsewhere.)

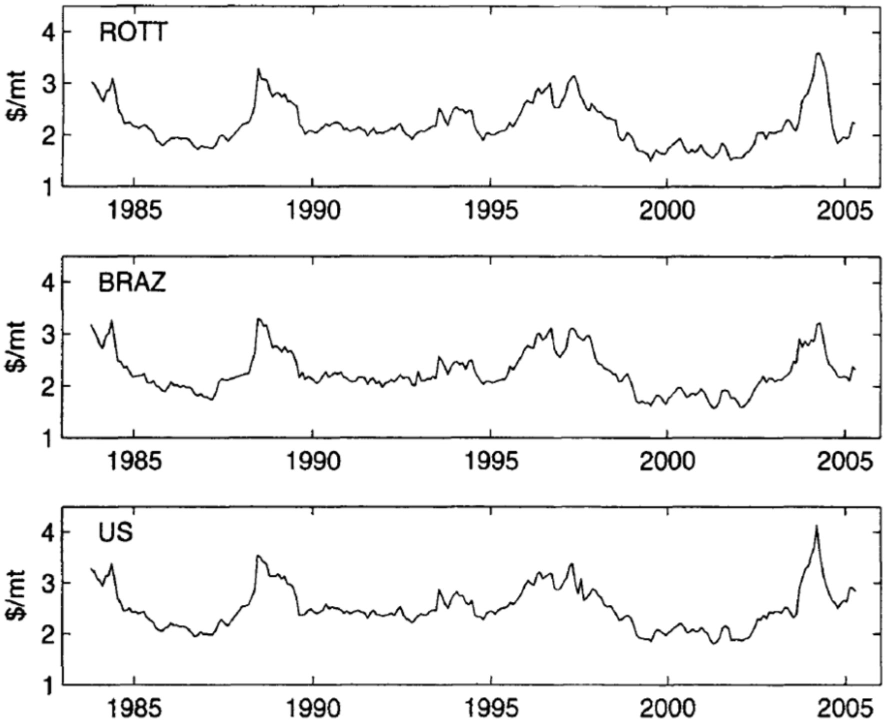
Overall, there is a lack of evidence to support the GTAP approach to agricultural trade, and a large well-cited literature that advocates very different approaches. These are important for ILUC. By artificially restraining trade effects in agriculture, GTAP is artificially restricting the international effects of biofuel policy.

Figure F1: Correlation of soybean oil futures and Malaysia palm oil futures



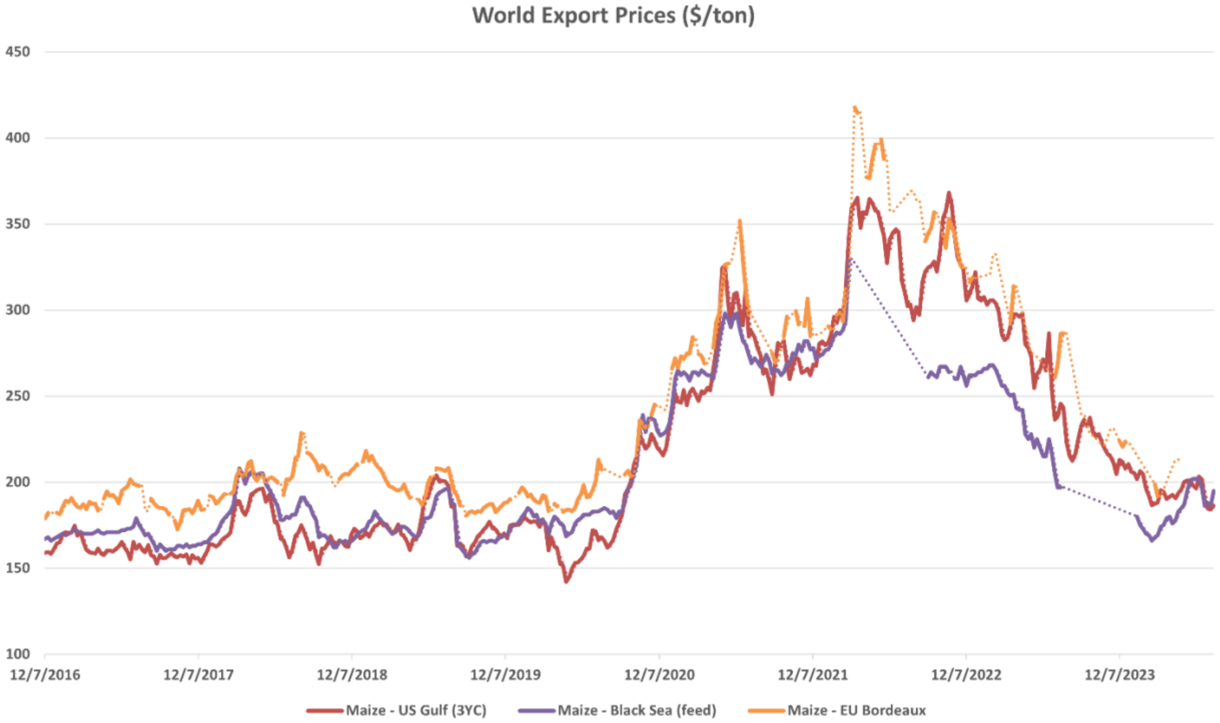
(Source: Reproduced from Reuters)

Figure F2: Correlation of soybean prices in Europe (Rotterdam), Brazil and the U.S.



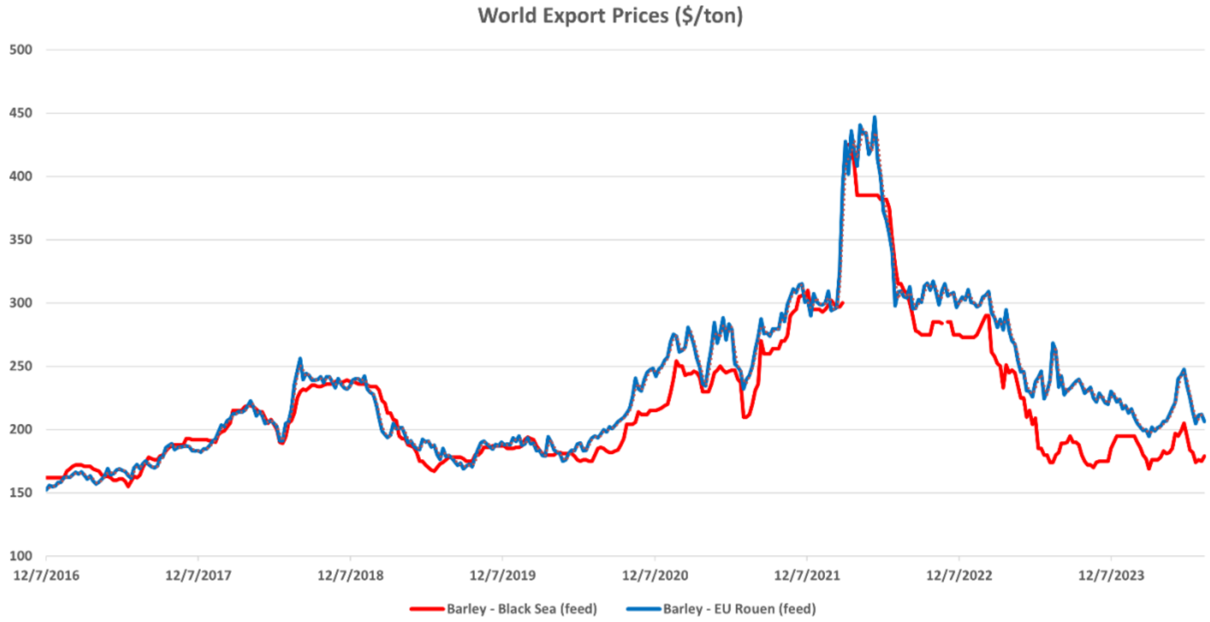
(Source: Reproduced from Fackler & Tastan [2008])

Figure F3: Correlation of world prices of maize from the U.S. (Gulf), the EU (Bordeaux), and the Black Sea (feed)



(Source: Authors' drawing based on data from the International Grains Council and FranceAgriMer)

Figure F4: Correlation of world prices of barley from Europe and Black Sea (Rouen)



(Source: Authors' drawing based on data from the International Grains Council and FranceAgriMer)

Figure F5: Correlation of U.S. biodiesel and net vegetable oil imports

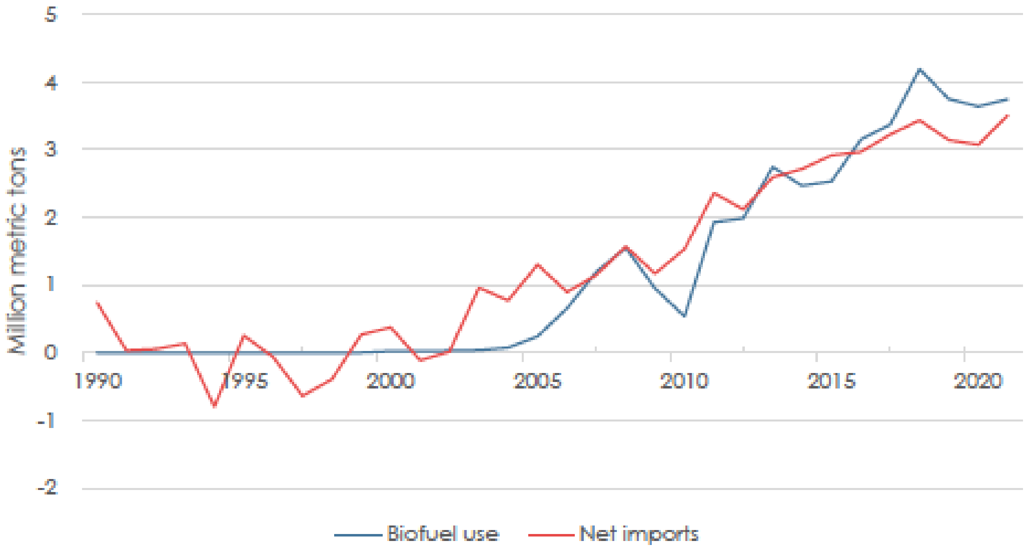


Figure 17. Increases in U.S. consumption of vegetable oils for biofuel production and in net vegetable oil imports, 1990 to 2021

(Source: Reproduced from Malins & Sandford [2022])

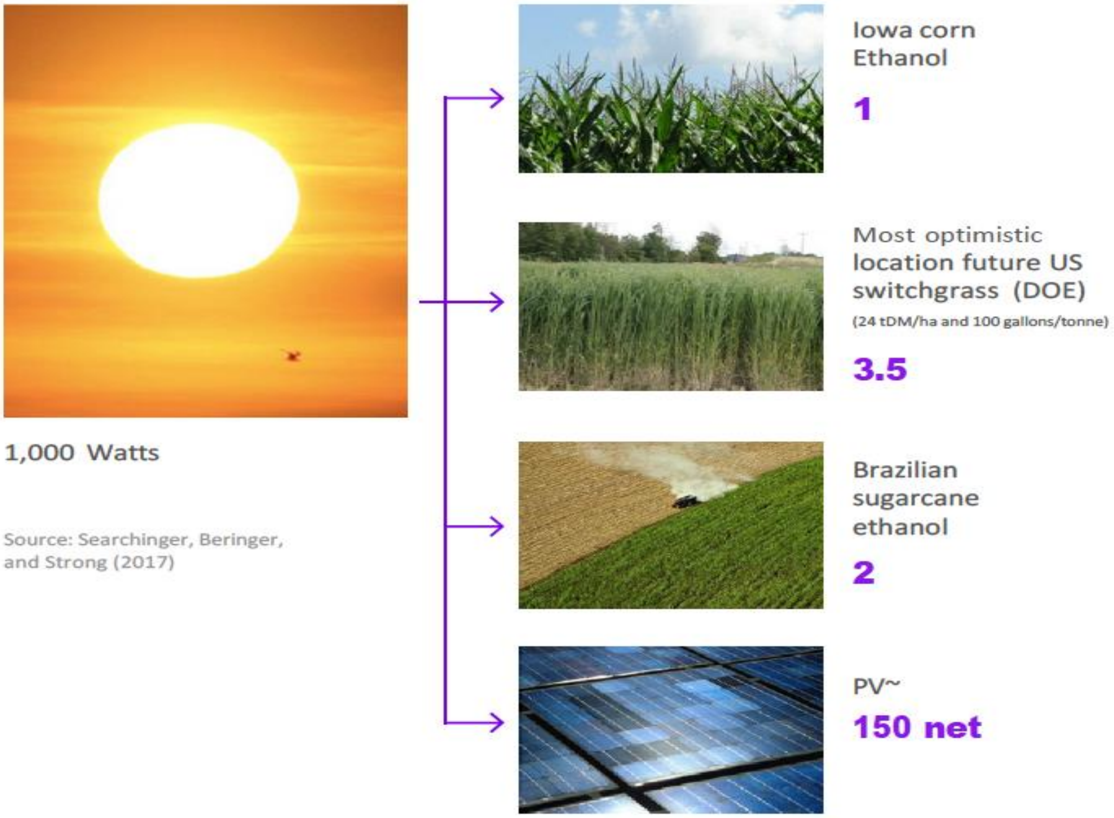
Figure F6: Parallel price movement of wheat in different regions

(Source: Authors' drawing based on data from the International Grains Council and FranceAgriMer)

Appendix G: Relative efficiency of conversion per solar watt and per hectare of biofuels and PV

Figure G1 illustrates the net efficiency of converting solar energy to energy in ethanol or in electricity as calculated in (Searchinger, Beringer, and Strong 2017). These net conversion efficiencies, which account for energy used in the production process for each energy source, are among the best scenarios for biofuels because they use highly productive, well-watered land in which crop production is high. On lower quality land, crop production declines but PV is unaffected. As discussed in that paper, use of electricity in an electric engine also increases the ultimate efficiency of driving per hectare used for energy production roughly three-fold.

Figure G1: Energy efficiency conversions



Source: Searchinger, Beringer, and Strong (2017)

(Source: Reproduced from (T. Searchinger 2023))