Towards an improved assessment of indirect land-use change

Evaluating common narratives, approaches, and tools

IEA Bioenergy: Task 43 - Task 38

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Evaluating common narratives, approaches, and tools

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Abstract

This report aims to evaluate approaches that are used to estimate the impact of increases in biofuel policy and production on food markets and land-use change by comparing their projections to statistical data on biofuel production, crop use, crop prices, trade, and land use. It presents an analytical framework that identifies routes via which increased biofuel production may affect crop and land markets. It distinguishes two alternative narratives that explain potential impacts of U.S. biofuel production on land-use change, each describing how corn use for ethanol production in the US can affect crop production in the US, and the consequences for global food and land markets. The analytical framework is applied to evaluate alternative approaches to assessing indirect effects including indirect land-use change. Alternative approaches and narratives are evaluated by comparing their projections with observations, based on statistics of ethanol production, corn production, corn use, and trade.

One narrative – focussing on changes due to biofuels on food trade and markets - assumes strong price responses to increased corn use for ethanol production in the U.S. According to this **trade and market response narrative**, the rises in national corn prices cause a decline in U.S. corn and meat exports, which will be compensated by enhanced crop production in main food exporting countries like Brazil where it will cause additional deforestation.

An alternative narrative – emphasizing internal adjustments and investments within U.S. agricultural systems - assumes sufficient flexibility within the U.S. agricultural sector to adapt and grow in response to planned increases in corn use for ethanol production. Consequently, the **internal adjustment response narrative** suggests increases in ethanol production have negligible indirect long-term impacts on food and land markets outside the U.S.

This report describes the narratives and reviews how they have influenced projections and calculations of the effects of biofuel expansion in the U.S. It focusses on the period after the introduction of the Renewable Fuel Standard (RFS) in 2005, evaluating studies that assess indirect effects of increasing corn use for ethanol production. It also reviews how causality of potential impacts can be tested when sufficient data are available. The **trade and market response** narrative links increased US ethanol production to local shortages, higher domestic prices, and the transmission of these effects to other markets (global markets and, via these, national markets in other countries). Studies applying the **internal adjustment response** narrative emphasize adjustments via choice of planted crops (planting more area in corn rather than sorghum and other crops), crop management (increasing yields), substitution and more efficient use (e.g., higher animal output per unit of feed enabled by protein coproducts from biofuels), among the many adaptations observed across the US agricultural system in response to targets to increase biofuel production.

Projections for corn use in ethanol production and associated changes in other corn applications, corn prices, trade and indirect land use effects of major studies are compared to each other and to statistical data. The comparison shows that some studies applying the trade and market response narrative overestimate ethanol and corn demand expansion; other studies overestimated short-term price changes in response to the RFS. However, corn price shows large variations over other time periods and longer-term analyses find that corn prices are driven by factors other than changes in biofuel production. The trade and market response narrative assumes that increased ethanol production creates an unanticipated "shock" in demand to an otherwise stable market equilibrium. However, the growth in demand was planned in advance and therefore predictable. Papers and reports that follow the trade and market response narrative have projected substantial disruptions of U.S. corn and other commodity markets, sustained price hikes, and large reductions in US crop and livestock product exports as a result of increased biofuel production in the U.S. These developments have, however, not been observed.

Studies applying the internal adjustment response narrative accurately projected expansion of corn ethanol output, and the flexibility of crop and livestock production systems to respond to increasing corn demand associated with biofuels policies. Some observed changes in US land use, such as increased cropping intensity, were predicted by internal adjustment response narrative; other changes observed

during this period, such as the replacement of barley and wheat by corn, were not anticipated in the studies that were analysed.

Biofuel policy assessment studies relying on general equilibrium models typically align with the trade and response narrative. They show large differences with respect to changes in U.S. food exports and, consequently, reactions in global food markets, which were the major instrument via which influence on land markets in countries like Brazil were projected (indirect land-use change). An analysis of historic data summarized in this report could not verify clear linkages between expanding U.S. biofuel production on the one hand, and corn production, corn export, or crop area expansion in Brazil. This result does not mean that such links could never occur, but it suggests that if they occur, they are much weaker than is often assumed.

Although a considerable number of studies were analysed in this report, there are limitations in the scope, which is restricted to one crop (corn), and one fuel type (ethanol) in one continent incorporating national annual data covering selected time periods, some being limited to only one decade. To determine the extent of indirect effects from biofuel production in a more generic way, it is recommended to expand the scope in future research. In the meantime, the interpretation of the effects of RFS should be revisited, as the majority of studies to date have applied the trade and market response narrative, which this study finds is inaccurate with respect to transmission of impacts on land-use in other countries.

The lack of consistency checks in studies examining the indirect land-use change effects of biofuel policy is remarkable, especially given the fact that the few causality studies that have been done fail to provide proof of the strong crop price changes and export volume responses that are central to the trade and market response narrative. A more robust, evidence-based method is needed to provide realistic assessment of if, when, and where indirect land-use effects occur, and to measure the corresponding impacts on carbon cycles and GHG emissions. A step to resolve this problem would be to conduct robust and direct field-based analysis of causes for each case where changes in land cover and land management present concerns. Future modelling could be improved by considering longer time periods of analysis, adjustments in crop and livestock production, on-going and cyclical dynamics in cropland and cropping intensity, crop choice, and trends for shifting and multiple uses of land for agriculture and other services.

An improved methodology to evaluate effects of biofuel policies on food markets and land management should have a more comprehensive scope. The degree of dynamics in demand, substitutions, and international trade of goods is not easily represented in simplified approaches that focus on an assumed change in demand for one variable while assuming other variables are held constant. It is recommended to include, at a minimum, the following elements in future analyses that aim to assess indirect effects of bioenergy policy on land use:

- Long-term trends for factors analysed, avoiding two-point comparisons
- Data on harvested areas and multiple cropping
- Crop yields
- Trends in seed, machinery, and labour input
- Full national land balances (accounting for all land in all classes, not just selected crops; and including grassland, forest and non-agricultural land cover)
- Trend data should consider the area planted in individual crops, secondary or cover crops, and management over 12-month agricultural years, considering rotations over time (crop matrix) for historic observations (baselines) as well as counter-factual and simulated scenarios
- Explicit long-term evaluation of changes in national and global crop prices and export volumes
- Causality checks (complete linkage, weight of evidence, etc.) of assumed relationships

1. Introduction

The ongoing debate on the impact that biofuel production has or may have on food availability and land-use change has not led to a consensus or the development of a common analytical framework. There is a lack of commonly agreed tools and data that could or should be used in the analysis. The way potential indirect effects (including indirect land-use change or ILUC) are quantified in tools and models has been criticized, authors questioning rationality of the approaches used as well as the outcomes. Critique focusses on the way land use and governance are covered (Kline *et al.,* 2011), the central role of economic modelling (Langeveld *et al.*, 2014; Ahlgren and Di Lucia, 2014) and lack of a causal analysis in models (Efroymson *et al.*, 2016) while uncertainty of the outcomes remains high (Plevin *et al.*, 2015).

De Rosa (2017) criticizes the truncation error introduced by processed-based life cycle assessment (LCA) studies, which necessarily exclude indirect effects, emphasizing that quantitative assessments are often incomplete. Breetz (2015) analyses how indirect land-use change science was interpreted and framed when the California Low Carbon Fuel Standard (LCFS) was developed in 2007-2009. In the process, stakeholders tended to mix values-based and science-based arguments. Even when stakeholders framed their positions as science-based, their interpretation of "right" action in the face of uncertainty remained based on normative values.

Several papers have discussed large variations in indirect land-use change estimates that have been published, and the tendency of more recent estimates to be lower than early values (Berndes *et al.*, 2013; Scully *et al.*, 2021). Reasons for this trend have been sought in increased land use, reduced model imperfections and, especially, better parameter values (Keeney and Hertel, 2009; EPA, 2010b; Scully *et al.*, 2021). In his analysis of the biofuels debate in the EU, Palmer (2013) describes the discourse on indirect land-use change, discursive activities and their role in the debate. Much of the controversy appears to be caused by the fact that indirect land-use change estimates from models cannot be observed or measured.

IEA Bioenergy Task43 (Biomass Feedstocks for Energy Markets) and Task38 (Climate Change Effects of Biomass and Bioenergy Systems) jointly studied relations between biofuel production from agricultural biomass, food and feed markets, trade flows and land use. The main aim of the study was to make an inventory of the way these relations are specified in existing research papers and models and to develop a framework for the testing if such relations can be observed in the real world.

This report presents the results of the IEA Bioenergy study. It compares methods that have been used in scientific papers evaluating indirect effects of U.S. ethanol production. The report develops an analytical framework to explain potential relations between domestic ethanol and feedstock production as well as distant (indirect) impacts. Two narratives are presented that characterize the way U.S. biofuel production could affect crop production and land use. The narratives are described and used to compare analytical approaches in assessing indirect effects including indirect land-use change.

The report is organized as follows: Chapter 2 presents the analytical framework and narratives for the assessment of indirect effects. Specific approaches to assess indirect effects are evaluated in following Chapters, including dynamic partial equilibrium models developed by the Food and Agricultural Policy Research Institute (FAPRI; Chapter 3), dynamic multi-product general equilibrium model approach of the Global Trade Analysis Project (GTAP; Chapter 4), a consequential LCA approach (Chapter 5), and an economic-equilibrium-extended LCA approach (Chapter 6).

The role of causality checks is discussed in Chapter 7. Results of the studies presented in Chapters 3 to 6 are compared to statistics of corn use for ethanol production, corn production, use and trade in the U.S. between 2005 and 2015 in Chapter 8. This is followed by a discussion and recommendations for an improved analytical approach (Chapter 9).

2. Analytical Framework

OVERVIEW OF FRAMEWORK

The analytical framework presented in this report identifies a number of crop, food, and ethanol production and trade activities in two countries, one where the biofuel policy is implemented, and the other where indirect effects may occur. Each group of activities is presented in a separate block (Figure 2.1). In total, nine blocks are identified. U.S. ethanol production, corn production, and use of corn feedstocks are depicted in the top half of the picture. These activities cover ethanol, corn, and livestock industries plus potential effects on land use, crop and food prices, and trade. The framework distinguishes activities that are directly involved or affected (depicted in yellow) and sectors or activities that are indirectly affected (blue).

The bottom half of the picture represents potential implications of U.S. corn use in ethanol production on crop production and land use in other countries. To simplify the discussion, all indirect effects are represented by changes that may occur in one country, in this case Brazil. In practice, of course, changes may be expected in multiple countries. This part of the picture presents many of the sectors that have been introduced in the top half of the picture, with exception of biofuel production (the analysis is restricted to US ethanol production), livestock production, and crop prices. Sectors or activities in Brazil are presented in green.

Each block contains several variables that may be evaluated while assessing (indirect) effects of enhanced U.S. biofuel production:

- Data on biofuels production including statistics on ethanol production and corn use in the ethanol industry (Block 1)

- Data on corn production such as harvested area, crop yield per ha, and corn output (Block 2)

- Data on cropland (available and suited for crops), grassland (pastures and other lands used for grazing), and agricultural areas (sum of cropland + grassland), plus forest area in the U.S. (Block 3)

Direct effects of biofuel policies are limited to (changes in) U.S. corn production and crop (corn) prices. Other effects in the framework are indirect. Some indirect effects may occur within the U.S. food production system, e.g., corn use in livestock production (Block 4), other crop production (not depicted here), and corn or other agricultural commodity trade (Block 6). The remaining blocks provide variables that monitor indirect effects in Brazil: corn production (Block 7), crop exports (Block 8) and changes in area for land cover (cropland, forest area, grassland, and other land; Block 9).

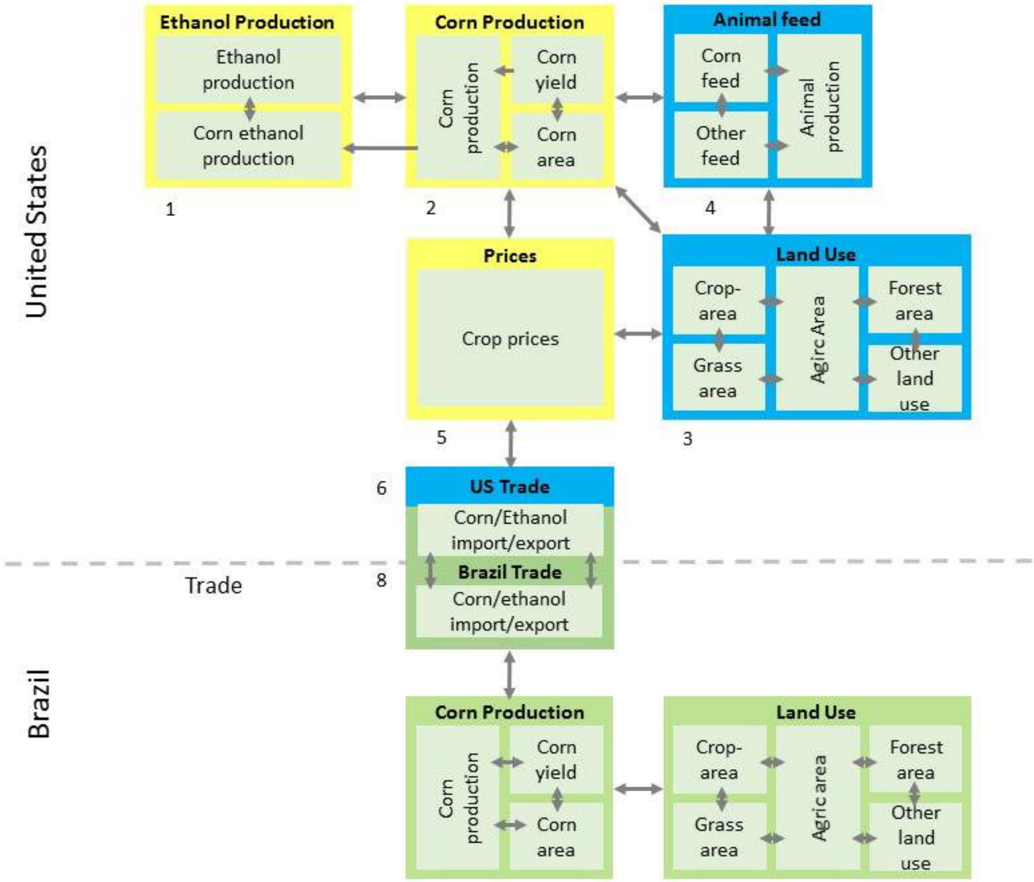

Figure 2.1 Analytical framework that links developments in US ethanol production to domestic and distant changes in corn markets, production, land use and trade. Domestic activities that are directly affected are depicted in yellow; activities that are indirectly affected are in blue. Activities in distant economies are presented in green.

NARRATIVES

The analytical framework is used to pinpoint the way different studies and reports evaluate potential indirect effects of U.S. biofuel policies and corn use in ethanol production. Our report focuses on two main narratives that have been presented and discussed by Langeveld *et al.* (2018). The first narrative assumes that biofuel policies provoke adjustments in global commodity markets and trade. The second narrative emphasizes reactions to biofuel policies that occur mainly in domestic food and feed production systems.

Trade and market response

The **trade and market response narrative** builds on the principle that crop output is adjusted to consumer demand. Responses to increased demand build on resources that farmers have at their disposal: capital and land. Farmers are expected to increase crop output by applying more inputs (capital), accelerating long term trends of gradual yield improvement. Demand that cannot be satisfied by yield improvement is considered to be covered by expansion of crop area.

As options for area expansion in the U.S. are limited by narrative design, farmers in other – distant – economies are expected to adjust their crop area in order to supply the feedstocks that have been diverted from food and feed production in the U.S. Crop expansion is linked to conversion of forest or grassland areas. Dominant mechanisms in this narrative are adjustments in crop prices and market shares that follow the diversion of corn to biofuel production; these signals are transferred from domestic markets to national and international markets.

The trade and market response narrative is a common framework for economic agricultural production models including Partial Equilibrium and Computable General Equilibrium models. Examples of applications of these approaches to assess indirect effects of biofuel expansion include Fargione *et al*. (2008), Searchinger *et al*. (2008) and Lambin and Meyfroidt (2011). The main concept of the narrative – biofuel production expansion leading to competition for feedstocks that cause price hikes – is used in most biofuel impact studies including the Food and Agricultural Organization of the United Nations (FAO) (2008 report on the State of Food and Agriculture), Nasser *et al*. (2011), and Hochman and Zilberman (2018). Arguments from these studies have been abundantly used in public debates on biofuels policies, especially when referring to 'food vs fuel' and deforestation effects.

Internal adjustment

An alternative narrative emphasizes the ability of U.S. crop and livestock production systems to respond to increased demand for corn by the ethanol industry in the same manner it adjusts to expected changes in demand by other sectors. In the **Internal adjustment narrative**, the production system is able to generate sufficient additional feedstocks to satisfy the need for biofuel production. Options to increase corn availability for biofuels are diverse and, in addition to raising farm input use, may also include (i) increasing cropping intensity or harvest frequency, (ii) investment in farm machinery and technical infrastructure, (iii) adjustments in specific crops grown each season (crop rotations or the share of major crops that are grown), (iv) substitutions and adjustments within and among diverse domestic use markets and sectors, and (v) increasing efficiency throughout the agricultural system.

Studies describing options to increase crop output include Lobell *et al*. (2009), Godfroy *et al*. (2010), and FAO (2009). Spiertz and Ewert (2009), Johnston *et al*. (2011), and Szabo (2019), and generally describe mechanisms for increased biofuel demand to trigger enhanced yield improvement and production efficiencies. Principles of the adjustment and innovation response narrative are found in studies examining impacts of biofuel expansion in the U.S. (Babcock and Iqbal; 2014), Argentina (Merlos *et al*., 2015), Brazil (Sparovek *et al*., 2016) and Hungary (Szabo, 2019). Global applications include FAO (2015) and Langeveld *et al*. (2014).

APPLICATION OF THE ANALYTICAL FRAMEWORK

Each narrative refers to specific elements of the analytical framework. The **trade and market response narrative** focusses on the way trade and markets are affected by the expansion of biofuel production in the U.S.: feedstock shortages leading to price changes, followed by shifts in trade flows that are transferred to national and international crop and food markets. While farmers are expected to increase their output, options to do so generally are considered to be limited, and a relatively high share of response is expected to come from market adjustments, both domestically and internationally.

Changes in crop prices are an important vehicle to transfer local effects to national and international markets, and papers from the market and trade response narrative tend to predict relatively strong changes in trade flows (exports or imports of crops and food commodities).

The **Internal adjustment response narrative** focusses on adaptations farmers can make - and are expected to make – in crop management, land management, and livestock production. It emphasizes farmers' ability and willingness to adapt production practices to changes in demand for crop feedstocks.

While taking steps to increase crop output, farmers initially remain within the limitations of their land resources; they make efforts to generate more crops from the land they have at hand, at least in the short run. Efforts to increase output can include a range of activities, including increasing fertilizer use or plant density, or stepping up control of diseases or weeds.

Alternatively, farmers may look to invest in drainage or irrigation facilities, in farm machinery or in storage or post-harvest treatment capacity. Farmers may also make changes in the crop matrix, increasing the share of crops that are expected to provide a higher per hectare margin, shorten fallow, or increase double cropping. Farmers may also adjust use of crops in animal production, for example by selecting alternative feedstocks (feed crops, roughage, or residues), increasing or limiting the use of corn in the diet, or alternative strategies in livestock production including shortening or lengthening the fattening period.

The expected changes in the agriculture – land – crops – livestock system under each narrative are depicted in Figure 2.2. Blocks that are expected to play a major role are highlighted in green. The Internal adjustment response narrative relates mostly to crop and livestock production (Blocks 2 and 3). Changes in crop prices and – especially – trade volumes (Block 5 and 6) play a more dominant role in studies that follow the trade and market response narrative.

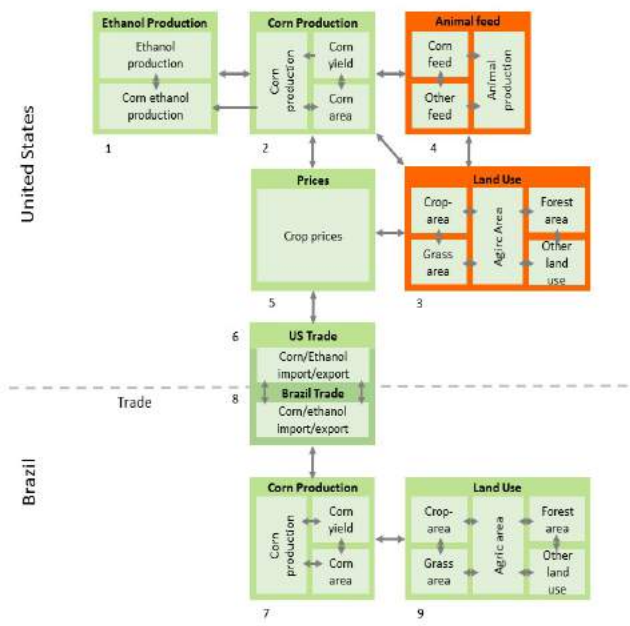

Figure 2.2a Main focus of the trade and market response narrative

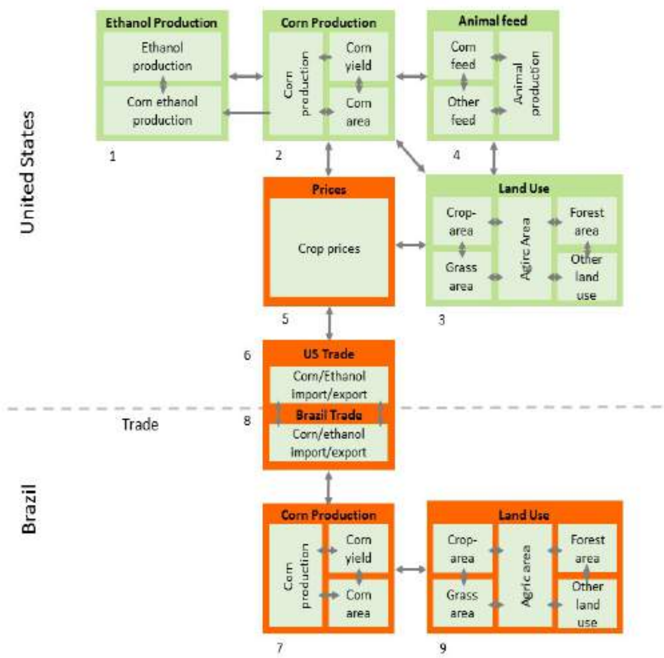

Figure 2.2b Main focus of the Internal adjustment response narrative

Figure 2.2 Activities typically evaluated in studies following the Trade and market response (2.2a) and the Internal adjustment narratives (2.2b).

CAUSALITY CHECKS

The narratives presented here are archetypes. It is not uncommon to find elements of both narratives in the same study. In practice, biofuel expansion is likely to not only affect crop and livestock production systems but also cause price effects and changes in trade volumes and market shares. In their analysis of the risks and prospects of biofuel production, the FAO discusses several options to increase crop output by – for example – adjustment of multiple cropping, while emphasizing risks of competition with food markets and price effects (FAO, 2008).

While economic studies are more likely to include more elements of the trade and market narrative, and agronomic papers tend to lean more heavily on technical adjustments and investment options that farmers have, this does not mean that all economic studies are predominantly focussing on price and trade effects. Nor do agronomic studies ignore such effects. In their review of instruments to quantify indirect land-use change effects of biofuels, Nassar *et al.* (2011) call for an approach that combines elements of both narratives while discussing their pros and cons. Dumortier *et al.* (2018) also present balanced views that combine elements of both narratives. However, our review of studies assessing indirect land-use change and indirect effects suggests that they often show a disciplinary bias.

Moreover, the fact that effects can be observed simultaneously does not automatically imply that there is a causal relation. There is a continuing call for the development and application of causality checks in the assessment of indirect effects caused by biofuels (Kim and Dale; 2011, Gawel and Ludwig; 2011, Oladosu *et al.*; 2011, Dale and Kline; 2013). Results of a study presenting causality checks of variables related to ethanol production in the U.S. are presented in Chapter 7.

3. Models developed by the Food and Agricultural Policy Research Institute

BACKGROUND

The Food and Agricultural Policy Research Institute (FAPRI) is a joint research institute focussing on the evaluation of agricultural policies in the U.S. and elsewhere. FAPRI was launched in 1984; it is established in the Center for Agricultural and Rural Development (CARD), at Iowa State University. Over time, researchers developed an extensive modelling system to monitor policy impacts on international agricultural commodity trade covering an increasing array of commodities and countries. The models that are developed here are often described as FAPRI-CARD models and can be characterized as dynamic, general equilibrium, multi-product, non-spatial, econometric-based modelling systems that provide commodity supply and use tables, price estimates, farm income and tax costs effects of policy scenarios.

In the models, national prices of country or regional models are linked to world market prices that are generated in the FAPRI world market outlook analysis. Model results are reviewed by modelers, industry, and government practitioners. FAPRI has a long history of evaluating domestic and trade policies in detail, providing policy impact analyses that closely reflect real-world conditions.

ANALYTICAL FRAMEWORK

Annual agricultural market outlooks (e.g., FAPRI-MU, 2020; USDA, 2022) focus on domestic crop and biofuel production, farm incomes and trade (Figure 3.1). Additionally, some papers cover impacts on distant economies, including crop production and land use (e.g., Elobeid *et al.*, 2012).

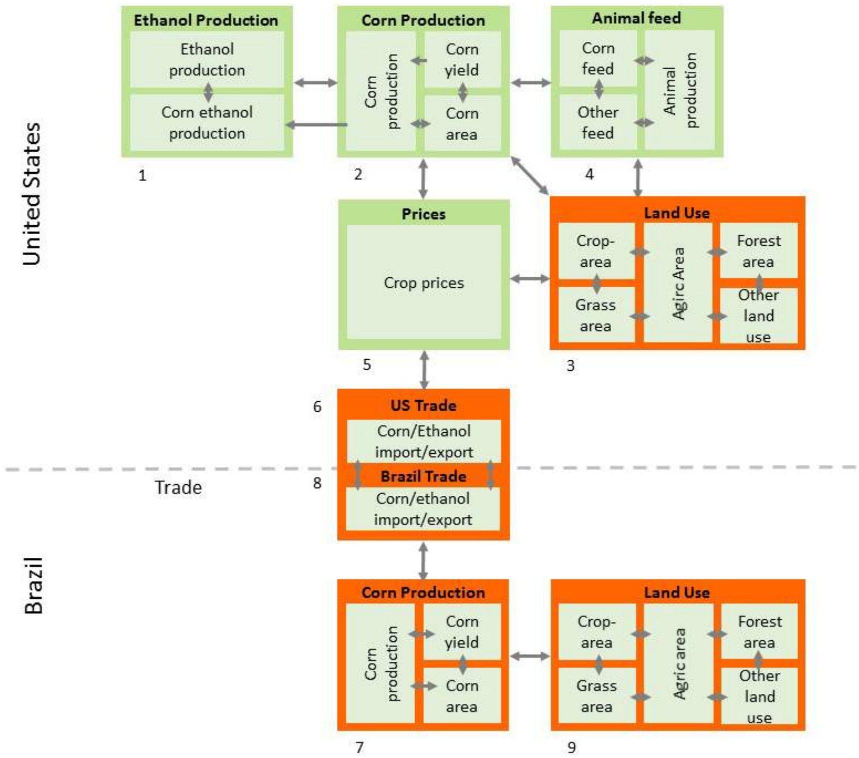

Figure 3.1 FAPRI monitoring and projecting U.S. ethanol (Block 1) plus elements of corn production (block 2), animal feed (block 4) corn prices and corn trade (blocks 5 and 6). Changes in U.S. land use (block 3), trade or changes in Brazil trade, production, or land use are not included

We analysed projections published in 2009 (FAPRI-MU, 2009), and compared them to observations (FAPRI-MU, 2020). For this study, we applied a simple mass balance approach to calculate increases of corn use in ethanol production and associated demand for extra corn. Main results are presented in Table 3.1

RESULTS

Projections presented in 2009 show that U.S. ethanol production in 2009 was projected to increase with 41.1 billion litres, virtually all from corn. Half of extra annual demand for corn feedstocks (95 million tonnes) was projected to be covered by an increase in domestic output (48 million tonnes in 2005-2015), facilitated by a slight yield improvement and expansion of U.S. corn harvested area by 3.9 million ha. A considerable amount of corn was projected to be diverted from the feed market (minus 23.6 million tonnes); no significant changes are reported in crop stocks or exports.

Table 3.1 Main impacts of increased ethanol production (FAPRI-MU, 2009)

Element (unit)	FAPRI data related to corn ethanol (2005-2015)
U.S. corn ethanol production (1)	Ethanol production to increase by 39.1 billion litres, virtually all from corn
Impact on U.S. corn production (2)	Additional annual demand is projected to be 94.7 million tonnes; yield increase 0.2 tonnes per ha, generating 9.2 million tonnes extra. Harvested area to expand by 3.9 million ha, covering 42% of increased demand
Impact on U.S. land use (3)	Not included
Impact on U.S. livestock production (4)	Drop in corn use in animal feed by 23.6 million tonnes, to cover 25% of increased demand.
Impact on U.S. crop prices (5)	Farm corn prices were projected to double in comparison to 2005 levels
Impact on U.S. trade (6)	Corn net exports were projected to change slightly (+0.7 million tonnes in 2015)
Impact on distant economies (7-9)	Not included

DISCUSSION

While there is no clear narrative in the data that are presented, the analysis focusses on changes in commodity markets and farm incomes. Data on crop area are limited to area planted or harvested; changes in other land cover categories or cropping intensity are not included in the analysis.

An evaluation of the FAPRI projections for the period 2005-2015, suggests that half of the increased corn demand was projected to be covered by a growth in U.S. corn output. Most of this was to be generated by area expansion; the remainder by yield improvement. Changes in corn feed use (to drop with 23 million) would cover a quarter of increased demand. Together, this would not fully cover additional ethanol corn demand.

No significant changes were projected in corn stocks or exports, suggesting that alternative sources would have to provide one quarter of increased biofuel corn demand.

4. Other examples of an equilibrium modelling approach

INTRODUCTION

Models originating from the Center for Agriculture and Rural Development (CARD) and the Food and Agricultural Policy Research Institute (FAPRI) at Iowa State evolved into a family of dynamic multi-product general equilibrium, non-spatial, econometric market models aiming to generate basic data on agricultural supply, price, income and taxpayer cost data for policy makers and stakeholders. The main focus is on detailed policy modelling linking national markets to global trade, based on public data availability, open-source modelling, and training in econometric approaches. One of the most influential biofuels policy papers was published by Searchinger *et al.* in 2008. The authors assessed the impacts of the growing corn ethanol production using general equilibrium, non-spatial, econometric market models developed at FAPRI-CARD.

ANALYTICAL FRAMEWORK

Trade model studies generally provide comprehensive evaluations of policy impacts, without including issues of land use or land conversion. Following the publication of the Searchinger paper, many papers were published that discussed theoretical and practical issues of evaluating indirect effects or establishing advanced assessments of GHG impacts (e.g., Keeney and Hertel, 2009; Taheripour and Tyner, 2011; Golub and Hertel, 2012). Such studies typically evaluate corn production, corn use in animal feed markets, land use, crop prices and corn trade, as well as distant corn production, trade, and land use, as is depicted in Figure 4.1.

Searchinger *et al.* (2008) compared two policy scenarios over the period 2004-2016: a base scenario and an alternative biofuels policy scenario generating an additional 56 billion litres of ethanol from corn. Impacts of the additional biofuel production were estimated based on the differences between the scenarios with respect to crop prices, animal feed availability, livestock production, and agricultural exports that are predicted by the model.

Reduced volumes entering the global crop and livestock markets are assumed to be compensated by farmers in distant economies. Impacts of subsequent need for additional cropland are assessed by calculating additional demand for cropland and carbon releases caused by conversion of forest and grassland areas. Finally, GHG impacts are calculated for crop production, conversion into ethanol, and burning in vehicles using the GREET emissions model.

RESULTS

Under the high bioethanol policy scenario presented by Searchinger *et al.* (2008), production of corn ethanol increases with an additional 56 billion litres. This leads to a strong demand for corn that is projected to lead to a peak in crop prices, which negatively affects livestock production (via animal feed markets) and agricultural exports. According to the authors, this will have huge implications for the global food system, causing a global decline of livestock consumption. Losses of export markets by the U.S.

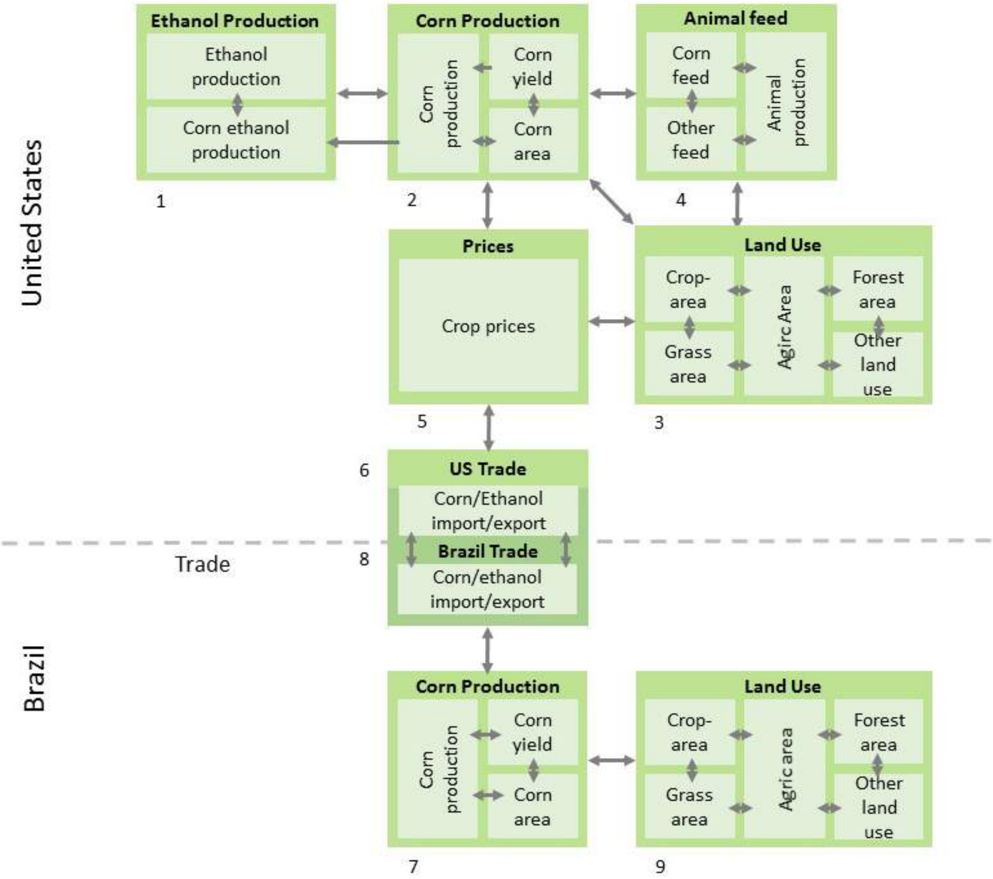

Figure 4.1 A trade model study assessing U.S. ethanol (Block 1) typically evaluates corn production (block 2), land use (block 3), corn use in feed (block 4) crop prices and corn trade (blocks 5 and 6), as well as distant corn production, trade and land use (blocks 7, 8 and 9, respectively).
Source: Based on Searchinger et al. (2008)

are projected to be compensated by enhanced output generated by farmers in Brazil and other agricultural hotspots including the EU, China, and India. The authors stress that yields in these countries are lower as compared to those in the U.S. and more land would be needed per tonne of corn. Additional demand for agricultural land is projected to provoke the conversion of forest and grassland areas into cropland. Searchinger *et al*. (2008) claim that the amount of carbon that is released because of land-use change would increase Brazil GHG emissions for decades. Main projections are presented in Table 4.1.

Table 4.1 Main impacts ethanol production according to Searchinger *et al*. (2008)

Statistics	Outcomes of the analysis
U.S. corn ethanol production (1)	Additional amount of corn-based ethanol of 56 billion litres
Impact on U.S. corn production (2)	Additional corn demand is 138 million tonnes; only 20% of which is covered by yield improvement. Corn area increases with 8.5 million ha, displacing wheat and soy production and

Statistics	Outcomes of the analysis
	exports
Impact on U.S. land use (3)	Growth of cropland by 2.2 million ha is projected. Increased ethanol production requires an additional 12.8 million ha of U.S. cropland
Impact on U.S. livestock production (4)	Livestock production suffers from high corn prices, caused by competition with ethanol production. Meat prices spike, forcing down demand and exports
Impact on U.S. crop prices (5)	Increase of domestic prices with 62% by 2015
Impact on U.S. trade (6)	Serious decline in exports (corn: -62%, wheat: -31%, soybeans: -28%, pork: -18%, and chicken: -12%)
Impact on distant economies (7-9)	Compensate for reduced U.S. exports by increasing crop cultivation in many countries, causing conversion of 10.8 million ha of land including China and India (2.3 million ha), Brazil (2.8 million ha) and Africa (0.8 million ha)
Carbon impacts (including indirect effects on land cover)	Strong growth in GHG emissions. Carbon footprint of corn ethanol including indirect land-use change is 177 gCO2eq/MJ

DISCUSSION

Most global equilibrium economic model studies are examples of the **trade and market response narrative**. For example, the Global Trade Analysis Project (GTAP), initiated in the 1990's, developed a modelling approach using econometric Computable General Equilibrium (CGE) models. Equilibrium models transfer the effects of biofuel policies – diversion of corn from traditional food and feed markets – to national and global commodity markets via price changes (see, for example, Searchinger *et al*., 2008; Keeney and Hertel, 2009; Valin *et al*., 2015; Taheripour *et al*. 2019). As supply is assumed to follow increased demand, the effects trickle down to land markets in countries that have land available for conversion into cropland such as Brazil.

The global equilibrium models in general, and the Searchinger paper in particular, rely on a market linkage framework to provide (additional) corn feedstocks. In this model, changes in U.S. corn production strongly affect domestic food and feed markets that, in turn, have considerable implications for exports, world markets and distant land use. This assumes that a price change in the US causes a response on distant agricultural frontiers. Changes in projected crop and meat prices caused by increased demand for corn suggest low elasticities for crop and meat demand in the model. The simulated changes in global corn production patterns, with distant economies compensating for anticipated drops in corn and meat exports by the U.S., are projected to have huge implications on land demand and land conversion in China, India and Brazil. The climate effects of the land conversions simulated in the model are extremely high.

The Searchinger paper has been highly influential but has also been criticized. Several authors using the same or similar models report lower GHG impacts. Keeney and Hertel (2009), for example, suggest that a higher share of the additional demand for corn could be met through crop yield increases; their LUC value estimate was 27 gCO2e/MJ, a quarter of the value calculated by Searchinger *et al.* (2008). EPA (2010a) reported lower indirect land-use change emissions than Searchinger due to including factors for improving crop yields and availability of distillers dried grains and solubles (DDGS) for livestock feed.

5. Consequential LCA

INTRODUCTION

LCA has been extensively used to evaluate effects of bioenergy policy support. LCA estimates environmental impacts associated with the whole bioenergy system or life cycle: extraction of raw materials, production of the crops/feedstocks, processing, distribution, and use. Two alternative approaches to modelling product systems exist: attributional (aLCA) and consequential (cLCA). While aLCA attributes a share of the global environmental impacts to the product system in a normative manner, consequential LCA aims to answer how the environmentally relevant flows change in response to a decision (Curran *et al.*, 2005).

Under the Revised Renewable Fuel Standard (RFS), the U.S. Environmental Protection Agency (EPA) conducted a full biofuel LCA explicitly including indirect land-use change-related emissions. EPA (2010b) estimated the climate impacts of direct, as well as indirect, GHG emissions associated with corn-ethanol production and combustion. While the EPA analysis reflected the best understanding of relationships between corn-based ethanol GHG emissions available at the time of publication, a large amount of additional information (scientific studies, data, technical reports, and emissions factors) has become available since then. In many cases, data have changed significantly.

More information on LCA methodology in biofuel impact assessments has been provided, see for example Taheripour *et al*. (2011) and Babcock and Iqbal (2014). Brandão (2022) used a consequential LCA approach to evaluate the U.S. mandate for producing 15 billion gallons of ethanol annually. It uses official statistical data on ethanol and corn production and includes substitution effects.

ANALYTICAL FRAMEWORK

Brandão (2022) assessed the implications of U.S. corn ethanol production, including changes in land use for the different corn uses, and implications on the markets for food, feed, vegetable oil and associated land use (Figure 5.1) using a consequential LCA approach aligned with the trade and market response narrative. Brandão (2022) used a market balance approach to quantify how changes in corn supply to the different uses was balanced in the different markets by marginal suppliers. Starting from U.S. statistics on ethanol production, compensation for corn diverted from food and animal feed markets was assessed taking into account yield and area increases in the U.S. Diverted corn was considered to be compensated by the marginal suppliers of food and feed. Land required for additional crop production was considered to be converted from forest or grassland or from existing cropland, depending on the land-use change matrix in marginal countries over the previous 20 years. Emissions of land-use change were quantified and used as input in the calculation of the GHG balance.

RESULTS

Under this approach, the use of corn for ethanol to meet the annual RFS2 requirement (15 billion gallons) is the start of a chain of responses. Sources of corn supply are the diversion of land from other uses and expansion for fuel, and implicit yield increases between 1999 and 2018.

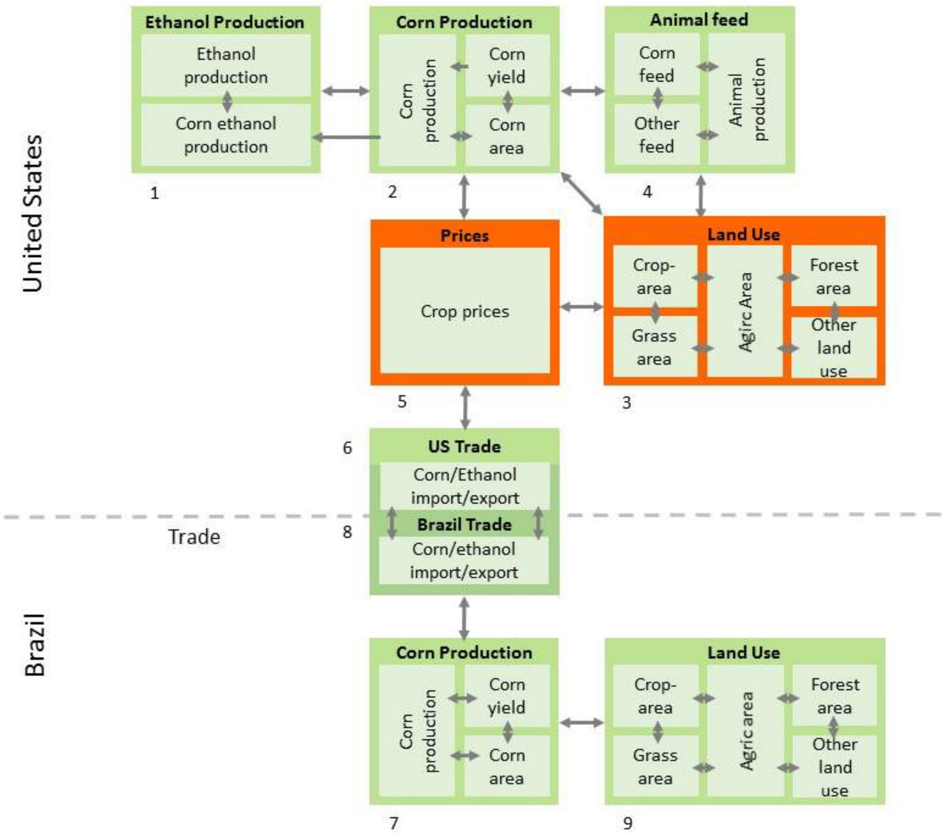

Figure 5.1 An LCA approach quantifying the impact of U.S. ethanol production (block 1) by evaluating changes in corn production (block 2), land use (block 3), trade (blocks 6 and 8), and distant crop production (block 7) and land use (block 9). Impacts on U.S. land use crop prices are not covered in the analysis. Source: based on Brandão (2022)

Additional demand for corn is 121 Mt, 56 Mt of which originates from increased domestic production. Another 44 Mt is diverted from animal feed; 9 Mt from food, and 7 Mt from exports. Production of DDGS is increased by 37 Mt. An overview of changes in crop production, use and trade is given in Figure 5.2.

Implications for land use in the U.S. are modest. While additional demand for corn area amounts to 5.2 Mha, 3.8 Mha of soybean area is released. Changes in cropland area outside the U.S. include increases in Russia (1.7Mha), Argentina (0.6Mha), Ukraine (0.3Mha) and Malaysia/Indonesia (1.3Mha). Conversely, Brazil experiences the avoided use of 4 Mha due to the balancing of the feed market, which displaces soybean production.

The production of 45.1 Mt corn ethanol substitute 28.0 Mt of gasoline, and thereby avoid the emission of 85.2 Mt CO2-eq. Despite the significant avoided emission of GHGs, as well as those from soybean production being substituted in both the USA and Brazil, the net level of GHG emissions is positive (by 18.0 Mt CO2-eq.) due to GHG emissions from ethanol processing and palm oil cultivation in South-East Asia, which are larger than the avoided emissions and therefore negate any climate benefit that substituting gasoline and soybean cultivation incurs. On net, these calculations find that corn ethanol has a carbon footprint of 105.1 gCO2-eq/MJ, which is 17% higher than that of gasoline (90.2 gCO2-eq/MJ).

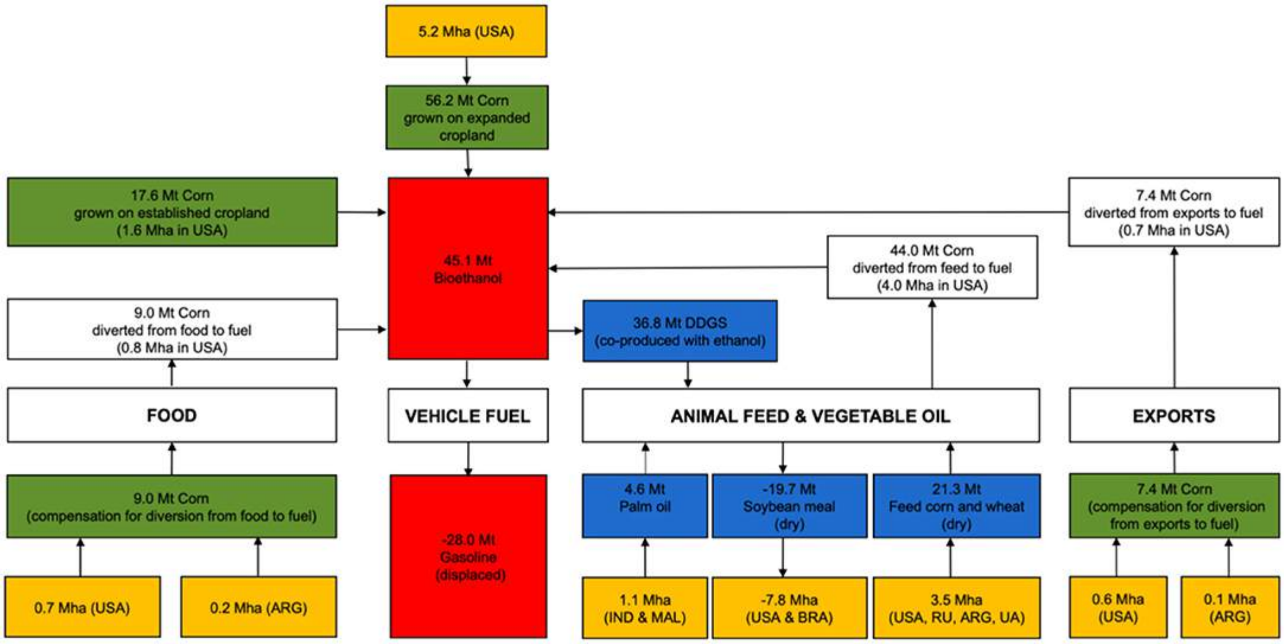

Figure 5.2 cLCA approach quantifying the impact of U.S. ethanol production by evaluating sources of domestic corn supply, domestic land use, balancing of feed and vegetable oil markets by marginal suppliers, and land use change in marginal suppliers (Brandão, 2022)

An overview of the results is presented in Table 5.1.

Table 5.1 Main impacts of increased ethanol production according to Brandão (2022)

Element (unit)	Outcomes of the analysis
U.S. corn ethanol production (1)	Increase in annual ethanol production by 15 billion gallons
Impact on U.S. corn production (2)	Additional annual demand for corn for ethanol production is 121 million tonnes, 56 million originating from additional production, and 44 million tonnes from feed use, 9 from food and 7 from exports
Impact on U.S. land use (3)	Growth of corn area by 5.2 million ha, release of 3.8 million ha of soybean land
Impact on U.S. livestock production (4)	44 Mt of corn diverted from animal feed. Corn ethanol generates 37 Mt of DDGS
Impact on U.S. crop prices (5)	No data presented

Element (unit)	Outcomes of the analysis
Impact on U.S. trade (6)	Loss of corn export by 7 Mt
Impact on distant economies (7-9)	Additional 4.8 Mt corn imports from Argentina, 4.6 Mt of palm oil (Indonesia and Malaysia), and 6 MT of corn and wheat. Net crop area decrease of 0.1 Mha (4 Mha released in Argentia, 3.9 Mha increase in other countries of which 4 Mha in Brazil)
Carbon impacts (including indirect effects on land coverindirect)	Land conversion causing carbon losses amounting to 18 million tonnes CO2-eq. Total emissions 105 gCO2eq/MJ of ethanol including indirect effects on land cover

DISCUSSION

Brandao (2022) quantified the amount of corn diverted from food, export and feed markets, based on a comparison of 1999 and 2018, assuming that those markets balance by increased or decreased production of marginal suppliers so that the assumed constant demand is met. Adjustments in crop production practices are excluded, although current yields are expressed which imply current practices.

LCA studies generally follow the trade and market response narrative, using a mass balance approach to quantify the amount of corn diverted from traditional food and feed markets and filling gaps in corn supply by trade (imports or reduction of exports). Adjustments in crop production practices are limited, as are options to make adjustments in animal feed markets. Land use is typically expressed in crop area, neglecting differences between harvested area and land cover.

The approach of Brandão (2022) relies on the assumption that all markets balance to compensate for a diversion of corn to the ethanol industry. It includes increase in corn supply to meet the RFS2 target of 15 billion gallons, which means 123 million tonnes of additional corn was needed. Of the total 134 Mt needed, this approach finds that about 13% is covered by land that was already under corn for ethanol in 1999, while 42% is covered via expansion of corn acreage on US agricultural land, the remainder to be provided for by diversion from feed (33%), food (5%), or export (7%).

Despite the increased demand for corn, no changes are anticipated in cropping intensity (double cropping, fallow) or crop matrix (e.g., replacing low yielding cereals by corn, which has a higher yield potential per ha), in addition to the implicit practices that led to the change of yield from 8.9 to 10.5 t/ha over the period. No changes in demand for livestock products are included. Price changes are not explicitly included either.

6. Extended LCA studies

INTRODUCTION

Alternative studies presenting extended LCA analyses of U.S. biofuel policy and corn ethanol production include Liska *et al*. (2009), Plevin (2009), Liska and Cassman (2008), Sinistore and Bland (2010), and Rosenfeld *et al*. (2018). Sinistore and Bland (2010) used a static framework, combining two calculation models to evaluate GHG impacts of ethanol production, using DDGS to replace existing feed crops in specific Wisconsin dairy farming systems.

A more generic LCA study has been presented by Flugge *et al*. (2017), who used updated datasets related to the life-cycle emissions for corn-based ethanol, assessing historic GHG emissions and projecting values for 2022 under a range of scenarios. The authors present industry trends, research on lifecycle assessment, land cover change, and other studies to provide an updated estimate of current and future ethanol emission profiles comparable to those developed for regulatory purposes by the US Environmental Protection Agency (EPA).

ANALYTICAL FRAMEWORK

The LCA model that was used quantified the impacts of U.S. ethanol production by evaluating potential changes in corn production and corn use (including animal feed). Indirect effects were monitored by evaluating implications for land conversion in distant economies. Less attention was given to domestic land use effects or price changes (Figure 6.1).

Flugge *et al*. (2017) evaluated regional land-use changes assumed to be caused by U.S. ethanol production. Their approach, characterized as consequential LCA, combines and updates the set of tools and economic models that have been developed by EPA (2010b). These include:

- **FASOM**, a partial forest and agricultural sector equilibrium economic model that projects changes in fertilizer and energy use, shifts between crops and changes in land use. GHG impacts of land-use change are calculated with emission factors
- **GREET**, the Greenhouse gases, Regulated Emissions, and Energy use in Transportation model tool providing crop and fertilizer GHG emission factors
- Livestock GHG emission factors published by **IPCC**
- **CENTURY and DAYCENT** models estimating impacts of N_2O emissions from fertilizer application
- **FAPRI-CARD** models of crop and livestock production. Land-use changes outside the U.S. and forest or pasture conversion into cropland are not provided. EPA (2010b) used satellite data analyses to estimate land conversion and associated GHG emission

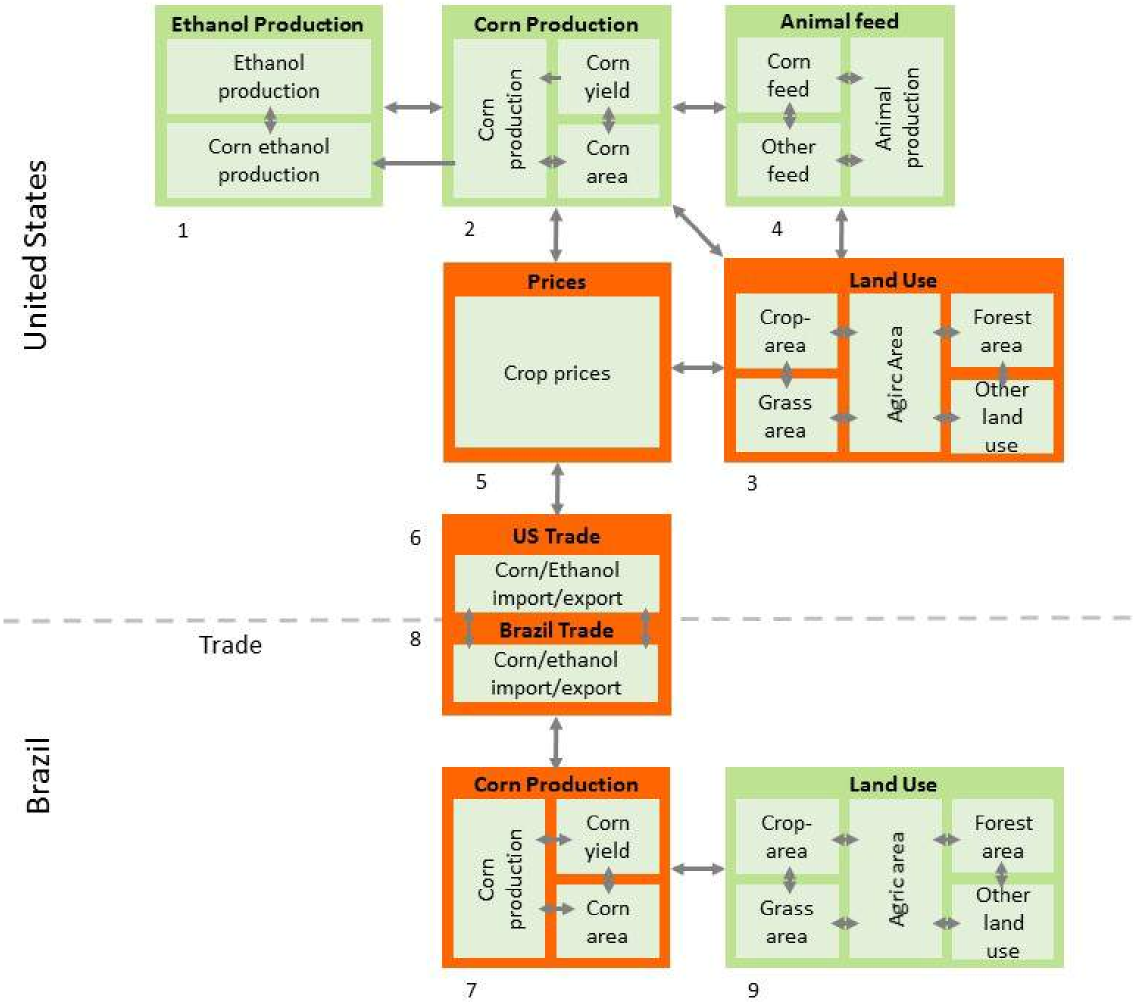

Figure 6.1 A consequential LCA study quantifying the impact of U.S. ethanol production (block 1) by evaluating potential changes in domestic corn production (block 2), animal feed (block 4) and domestic as well as distant land use (block 3 and 9, respectively). No reference is made to land-use changes in the U.S., or adjustments in crop prices, trade volumes, or distant crop production.

Source: Flugge et al. (2017).

A scenario approach was used by Flugge *et al.* to evaluate the effects of ethanol production attributed to the RFS by 2022, considering a set of emission factors and reviewing earlier assumptions on issues such as double cropping, residue management, reduced tillage, improved nitrogen fertilizer management and use of cover crops. Estimations of international land-use change are based on assessments presented by CARB (2015) and Dunn *et al.* (2014). Emission factors incorporated in the study include:

- Domestic land-use change
- Domestic rice methane
- Domestic livestock
- Domestic farm inputs and fertilizer N_2O
- International livestock
- International land-use change
- International farm inputs and fertilizer N_2O
- International rice methane
- Fuel and feedstock transport
- Fuel production
- Tailpipe emissions

RESULTS

The Flugge *et al*. analysis noted that ethanol production was anticipated to increase by 44 billion litres in 2022 over the 2004 capacity levels, of which 9.8 billion litres were attributable to the RFS. The study examined a range of ethanol yields per ton of corn and other variables that influence calculations of effects of US ethanol production. The best available, current data were assembled from government supported studies and data. In an optimized 2022 production scenario, projected corn yield per ha increases (+12% in a period of nine years) and this was expected to cover 80% of the increased demand. Increases in efficiency, primarily in corn-to-ethanol conversion factors in new mills, were responsible for meeting the remaining demand. Aligned with USDA baseline agricultural projections, ethanol and other market demands are met as US corn acreage increases initially, then levels off and declines slightly, as total US cropland area also declines slightly.

Impacts of the expanding ethanol and coproduct outputs such as high-protein distiller's grains for animal feed, affect livestock production (a small increase in beef cattle numbers is projected while other livestock numbers were expected to decline). Trade reflects growing exports of distiller's grains.

Impacts on land use outside the U.S. were examined based on GTAP-2013 (Taheripour and Tyner 2014), Dunn et al., (2014) and Babcock and Iqbal (2014). Flugge et al. integrate these sources and estimated that net global cropland area increased by 214,000 ha per GTAP-2013, but only 51,000 ha when GTAP-2013 is adjusted based on the analysis of double cropping produced by Babcock and Iqba. Babcock and Iqba explained how models reporting harvested acres over-estimate land area as they omit double cropping (harvesting more than one crop in a calendar year) which was found to be increasing in response to enhanced demand for corn between 2004 and 2012 and a continuation of this process was projected.

In the GTAP-2013 and subsequent estimates of indirect land-use change reviewed in Flugge et al., nearly all global crop expansion occurs on grasslands and cropland-pasture in sub-saharan Africa and Brazil. Combined effects of changes in land use, manure management, and cropping intensity have been used to assess the GHG footprint of ethanol production in 2022. An average value for land-use change emissions was calculated at 8.6 g CO_2e/MJ, a fraction (29%) of the original EPA (2010b) estimate of 30 gCO2e/MJ.

Main results are presented in Table 6.1.

Table 6.1 Main impacts of increased ethanol production according to Flugge et al. (2017)

Element (unit)	Outcomes of the analysis
U.S. corn ethanol production (1)	Ethanol production increased by 44 billion litres between 2004 and 2022, virtually all from corn
Impact on U.S. corn production (2)	Additional corn for ethanol is 55 million tonnes. Yield increases from 10.1 to 11.4 tonnes per ha (12%), generating 44 million tonnes in 2022. The remainder is sourced primarily by improved corn-to-ethanol conversion efficiencies based on improved technologies in new mills.
Impact on U.S. land use (3)	Corn area expands with 2 million ha in 2013, then a slight decline (-0.4 million ha) to 2022. Increased use of no-till and conservation tillage is also associated with increased ethanol production (a change in domestic land management). Total US cropland area changes only slightly (0.05 m ha) by 2022.

Element (unit)	Outcomes of the analysis
Impact on U.S. livestock production (4)	Reduction of poultry and dairy, increase in beef cattle. Impacts of adjusted feed use and manure management on methane emissions are included in the GHG calculations
Impact on U.S. crop prices (5)	Not included
Impact on U.S. trade (6)	Exports of distillers grains increased by 8.2 million tonnes (2008 to 2015) and projected to continue
Impact on distant economies (7-9)	Growth of harvested area is mostly met by increasing double cropping (Brazil:76%, China 29%, India 100%)
Carbon impacts (including indirect effects on land cover)	Conservation tillage and improved nutrient management increase soil carbon gains. Corn ethanol emissions footprint is low (25 g CO_2e/MJ). Using the average value calculated from seven distinct methods, GHG impact from indirect land-use change is calculated at 8.6 g CO_2e/MJ.

DISCUSSION

The report by Flugge *et al.* (2017) does not use a typical LCA approach or unilaterally apply the trade and market response narrative. Evaluation of local variables and implications for US corn production and use is followed by an assessment of GHG emissions associated with all aspects of the supply chain, including indirect effects. Indirect effects are calculated by assembling the best available data at that time from various sources but primarily GTAP and the mass balance approach reflected in Babcock and Iqbal (2014). Innovations in crop management – reduced tillage, improved nutrient management, and cover crops – are considered in the calculation of GHG impacts. Price and trade volume adjustments are not quantified.

Scenario results are based on a range of new insights developed since publication of an EPA study in 2010, which suggest improvements in farming practices, land use (double cropping), crop yields, and bio-conversion technologies in new ethanol mills, can provide the corn required for ethanol production in 2022 with some land to spare (a slight reduction in total US cropland). Changes in livestock numbers are projected due to increased protein in distiller’s grains.

Undesired indirect effects are mitigated by an anticipated increase in double cropping and improved yields. In Brazil, double cropping is estimated to provide up to 76% of additional crop output associated with the GTAP-2013 simulated land requirements associated with increased U.S. ethanol production. The effect is not equal across all countries, with China showing lower potential to increase double cropping, while India may have a larger potential.

The study presents an extensive listing of outputs and projections reported in other studies that is meticulously analysed. The estimated impacts of improved crop, nutrient, and manure management are large. Thus, when good management practices are employed, the estimated GHG footprint for U.S. ethanol in 2022 is a fraction of the value calculated by Searchinger *et al*.

7. Causality analysis studies

INTRODUCTION

Pure examples of the internal adjustment response narrative are rare. Elements of this narrative can be found in Kim and Dale (2011) who evaluated potential indirect effects of U.S. corn ethanol production. The authors used a bottom-up, statistical approach for an empirical ex-post evaluation in order to detect evidence for potential indirect land-use change caused by U.S. corn ethanol production increases between 2002 and 2007. The paper does not, however, quantify implications of biofuel production. Instead, it tests whether indirect effects can be identified.

A similar approach has been used by Oladosu *et al.* (2021). Building on the premise that economic theory assumes causal relationships between crop supply, demand, and prices, the authors set out to examine assumed causality in the context of indirect land-use change. They applied statistical analysis tools including the identification and analysis of unexpected changes in long term trends (structural breaks) in data sets, and so-called Granger causal analyses, to explore the relationships of U.S. corn and ethanol production with fossil and crop prices, non-ethanol (e.g., feed) use, and exports.

ANALYTICAL FRAMEWORK

In the causal analysis study of Oladosu *et al.* (2021), the relation between changes in U.S. ethanol production (Block 1) and domestic corn production, animal feed, and trade were tested. The study assessed long-term data for U.S. ethanol production and domestic corn production, animal feed and trade, but did not analyse land use. Relations with distant corn production, land use, or trade were not assessed. Instead, this study tested validity for underlying drivers of indirect land-use change that are presumed in other approaches, such as impacts on prices and US exports. A graphical representation of a typical causality analysis is presented in Figure 7.1.

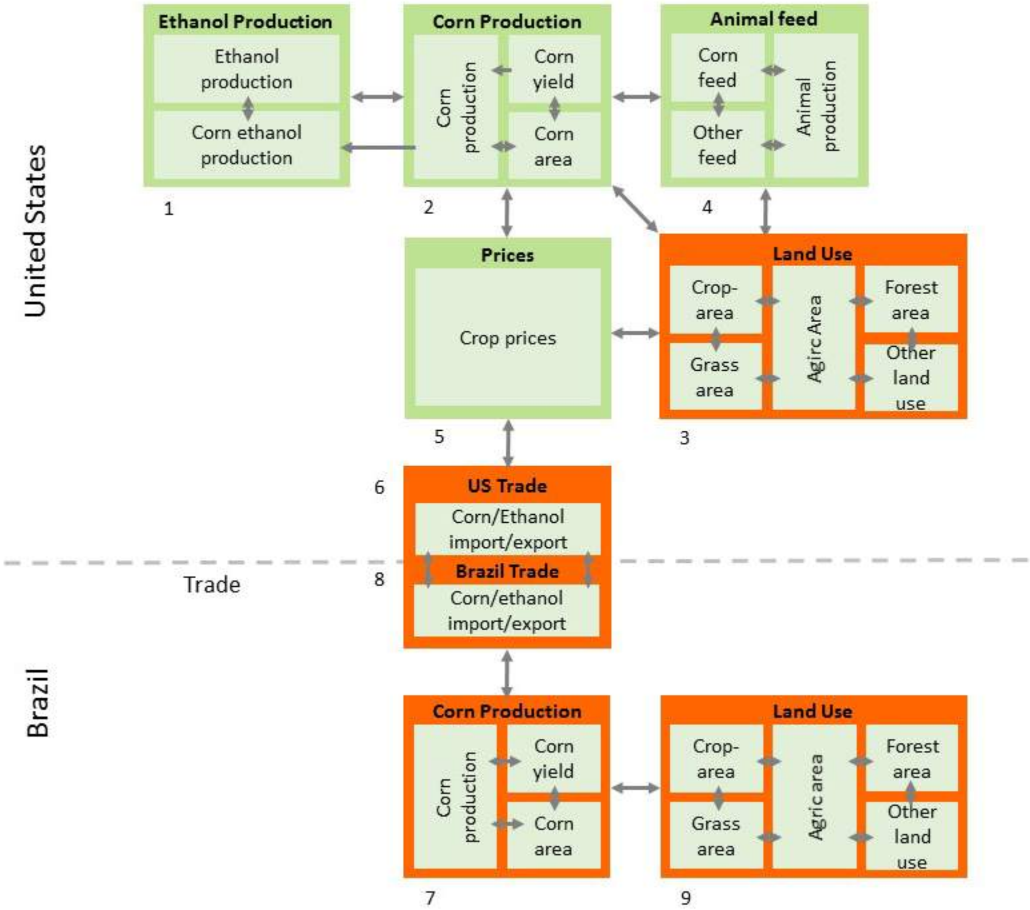

Figure 7.1 A causal analysis study may assess the relation between U.S. ethanol production (block 1) and domestic corn production (block 2), animal feed (block 3) and trade (block 6), but not land use (block 3). Relations with distant corn production, land use or trade (blocks 7, 9 and 8, respectively) are not evaluated. Source: based on Oladosu *et al.* (2021).

The authors applied a Granger-causality framework, a common approach in economic causality analysis which can evaluate multivariate data. Starting with the fact that an effect cannot precede its cause, causality of changes in one variable (e.g., increase in corn ethanol production) and effects on potentially dependent variables (e.g., corn acreage, production, domestic use, prices, and exports) were systematically tested. Causality tests were run for synchronous and lagged causal relations. Quarterly statistical data on U.S. corn supply and use were analysed for the period 1999-2017. No foreign data were included in the analysis. Prior to the analysis, a structural break analysis was used to identify significant shifts in the data. Granger-causality tests were performed using bivariate augmented-VAR (vector auto-regression) models.

An overview of the causality checks that were done is presented in Figure 7.2.

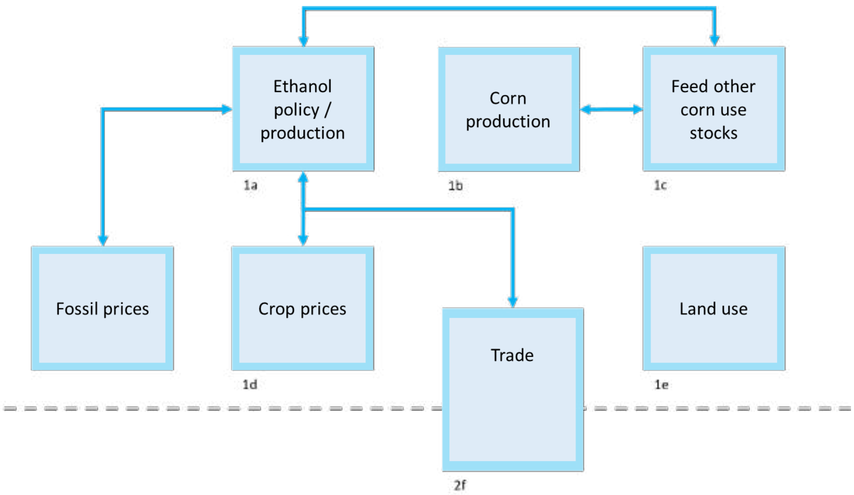

Figure 7.2 Causal analysis evaluation presented by Oladosu et al. (2021)

RESULTS

Ethanol production and corn exports are linked to corn stocks, with high availability stimulating both exports and ethanol production. Some evidence was found that high ethanol production is linked to reduced domestic non-ethanol corn use, implying that production of ethanol and coproducts such as distiller's grains may reduce direct use of corn for feed.

No structural statistically significant causal relations were found between corn ethanol production and corn prices. Extensive interactions were observed between corn use for ethanol, total domestic corn consumption, and other domestic corn use. Between 2005 and 2010, for instance, corn used for ethanol more than tripled, whereas other domestic uses declined by 17%. A previous analysis (Oladosu *et al.*, 2011) suggests that reduction in other domestic corn use might be traced to an increase in corn use for ethanol demand. Results imply that the interrelationship between these two variables is not straightforward.

Results of the study are presented in Table 7.1.

Table 7.1 Main impacts of increased ethanol production according to Oladosu *et al.*

Element (unit)	Results presented
U.S. corn ethanol production (Block 1)	Structural breaks in data for corn ethanol use appear to be associated with periods of debate on legislation, corn price spikes, and drought. High ethanol production is significantly linked to increases in corn supply.
U.S. corn production (2)	The analysis suggests decision making on using corn for ethanol is policy driven rather than market driven. Between 2005 and 2010, use of corn for ethanol increased from 41 to 128 million tonnes

Element (unit)	Results presented
U.S. land use (3)	Not assessed
U.S. livestock production (4)	Between 2005 and 2010, ‘other’ domestic corn use declined by 32 million tons. High corn ethanol use is linked to reduced direct use of corn for feed
U.S. crop prices (5)	No evidence found of a causal impact of corn use in ethanol production and use on crop prices
U.S. corn trade (6)	No causal relation was found between corn ethanol use and corn trade (exports)
Distant impacts (7-9)	Impacts of U.S. ethanol production on crop production and land-use change in Brazil, for example, were not assessed but assumed underlying drivers for indirect effects, e.g., changes in price and exports, are found to merit revision.
Carbon impacts (including indirect effects on land cover)	No assessment was made of indirect land-use change or its impacts on ethanol GHG emissions

DISCUSSION

The paper by Oladosu *et al.* (2021) does not specifically implement either of the two narratives that have been presented above. Instead, the structural break and causality analysis were used to test causal relations that are assumed to exist between corn use in ethanol production and (i) corn use in animal feed, (ii) crop prices, and (iii) corn exports, indicators that are used in the demand driven commodity markets narrative.

Strong dependencies that are often assumed (e.g., between ethanol production and crop prices, export volumes, and corn feed use) could only partly be confirmed. The analysis of historic data did not support assumptions for corn ethanol production and use to lead to higher crop prices or lower exports. The link between ethanol production and exports on the one hand, and high corn stocks on the other hand, was identified and deserves further exploration.

There is a link between ethanol production and corn use in animal feed. However, the link is not as strong as one might expect. Several studies discuss the impact of an import ban in major Asian markets on U.S. meat in 2002 as a cause for reduced livestock production. Others claim the stagnation in U.S. cattle output between 2005 and 2007 was caused by shifting preferences away from red meat, and the discovery of mad cow infections.

Adjustments and interactions between corn supply, other corn uses, and beginning stocks appear to account for the corn use for ethanol production. Generation of DDGS ensures that 30% of corn used for ethanol is returned as high-quality feed, reducing demand for direct use of corn for animal feed. Consequently, the quantity and quality of enhanced DDGS availability seems to have made up for nearly all the reduction in other domestic corn uses between 2005 and 2010.

The results shed new light on the discussion on indirect effects of biofuels. U.S. ethanol production apparently did not affect corn exports, which means that the assumption that ethanol production causes a drop in exports, which need to be compensated by other countries, needs to be reconsidered. Also, the lack of a causal relationship between use of corn for ethanol and corn prices challenges the common narrative that biofuel production is a major source of crop price increases.

8. Analysis: the impacts of expanding U.S. corn ethanol production

INTRODUCTION

This chapter discusses U.S. corn use for ethanol production since 2005 and possible impacts this may have had on corn production, use, and trade as well as land use in the U.S. and Brazil. It presents data from major national and international statistics.

Ethanol and corn production

U.S. ethanol production increased from 16.4 billion litres in 2005 to 53.1 billion litres in 2015. The amount of corn used for ethanol rose to 60.8 million tonnes. Following enhanced demand, corn production grew with some 25% to 346 million tonnes in 2015. Average corn yield and harvested area, 9.3 metric tonnes/ha and 30 million ha in 2005 had risen to 11.6 tonnes/ha and 33 million ha in 2015, an annual average increase of 0.18 tonnes/ha/year and 0.38 million ha harvested area (Figure 8.1).

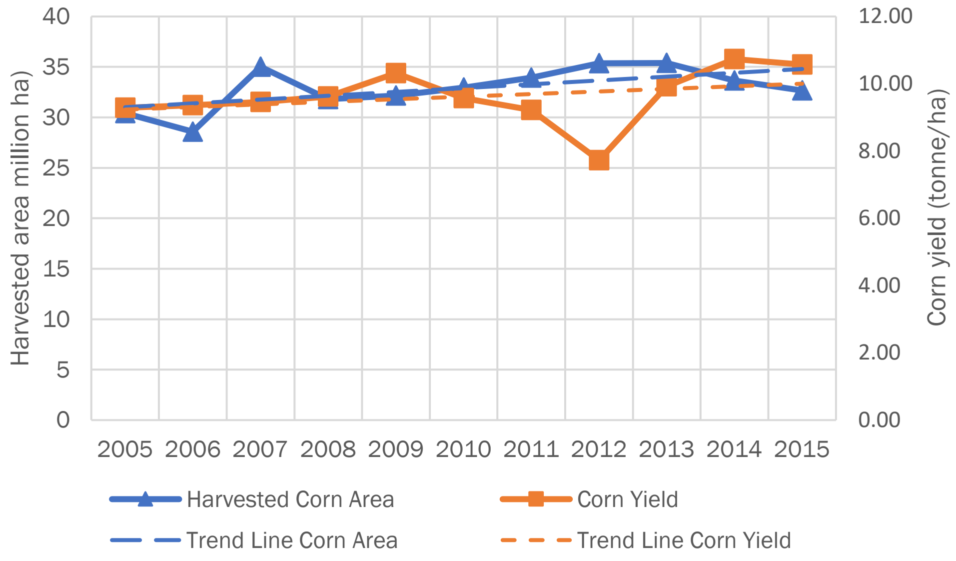

Figure 8.1 Corn yields and harvested corn area in the U.S. (2005-2015). Source: USDA (2020).

Output growth was not sufficient to cover the additional demand for corn by the ethanol industry; an estimated 60% has been covered by increased corn output. The remainder has been covered by other sources, including adjustment of corn use in livestock production.

Animal production

According to FAPRI-MU, use of corn for animal feed declined by 20 million tonnes between 2005 and 2015. Availability of DDGS, on the other hand, increased by almost 29 million tonnes (USDA, 2022). The value of DDGS in animal feed is similar to that of corn (during ethanol production only carbohydrates in corn are removed, but no other elements). As a result, DDGS is lower in starch but higher in oil, proteins and essential nutrients, making it a powerful animal feed or supplement. Thus, these data do not support assumptions that the animal production sector in the U.S. was seriously impacted by the use of corn for ethanol. FAO data show that meat production in the U.S. did not suffer. On the contrary, total (beef, chicken, pig, and sheep) meat production increased by over 4.5 million tonnes. This was supported by increased DDGS and oilseed cake production (28.8 and 17.3 million tonnes, respectively).

Land use in the U.S.A.

U.S. land use data since 2005 show that increases in corn cultivation did not lead to an expansion of crop area, which declined by 13 million ha. This decrease is four times greater than the increase of corn harvested area, as shown in Figure 8.2. Some cropland transitioned to perennial grassland (+7 million ha) and forest area (+3.7 million ha).

Crop and food prices

After a price spike between 2005 and 2008, corn prices dropped in 2009. They went up again during the drought of 2012. Since then, prices show a steady decline, reaching a level in 2017 that was some $70/tonne higher than it was in 2005. However, the 2017 level is nearly the same as corn prices observed in 1996 (more than 20 years earlier).

Trade

The impact of a growing corn-based ethanol industry on corn trade has been surprisingly low. Exports were relatively steady 1999-2005, then increased with rising corn use for ethanol from 2005-2010, returning to the 2005 level in 2011. When the country was confronted with record adverse (drought) conditions, net trade in U.S. agricultural commodities including corn declined (2012-2013). Exports have recovered quickly since then. No clear downward trend attributable to ethanol production has been observed in the historic data (Figure 8.2).

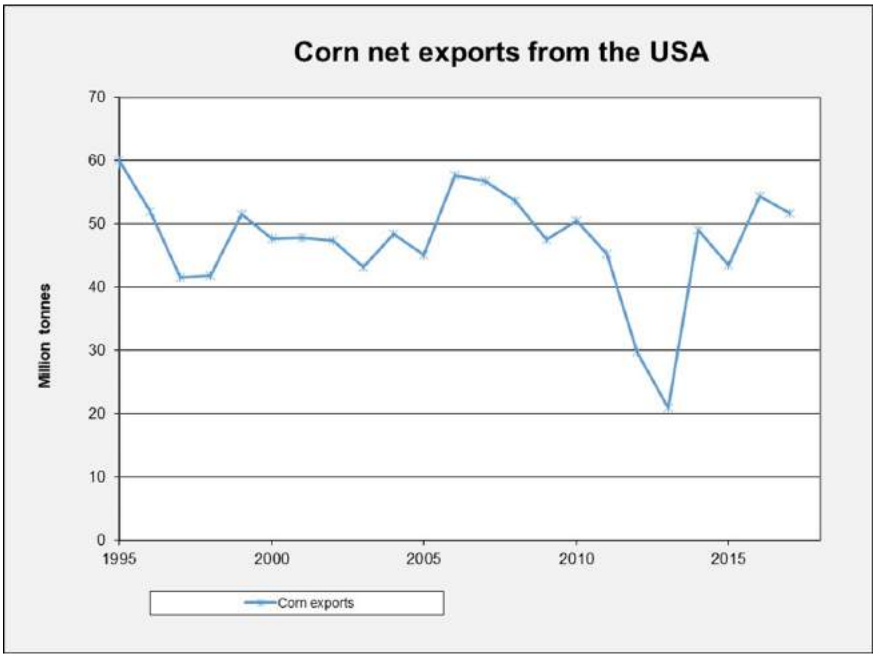

Figure 8.2 U.S. feed imports in the U.S. (2005-2015). Source: FAOSTAT (2020).

Brazil crop production and exports

Corn production in Brazil went up from 35 million tonnes in 2005 to 85 million tonnes in 2015. This increase has been supported by a strong improvement of yield levels, which almost doubled. Harvested area increased by 3.9 million ha, but a large share of this harvested area occurred as a double crop with soybean production and did not require expansion. Exports increased from less than half a million tonnes in 2005 to nearly 29 million tonnes.

Brazil land use and carbon effects

FAO data show an increase of corn harvested area of 3.9 million ha since 2005. Agricultural area has grown by 6.7 million ha; half of this is permanent grassland. Forest area loss accounts to more than 27 million ha, which means that 25% has been converted into agricultural land, mostly to grassland.

Summary

A summary of the U.S. corn ethanol expansion and its main impacts are presented in Table 8.1.

Table 8.1 Main impacts ethanol production in the U.S. and Brazil

Statistics	Effects
U.S. corn ethanol production (Block 1)	Ethanol production increased by 36.8 billion litres, mostly corn-based
U.S. corn production (2)	Corn demand increased by 91.5 million tonnes, domestic production by 63 million tonnes. Yields improved by an average of 1.3 tonnes per ha. Corn harvested area expanded by 2.9 m ha
U.S. land use (3)	Grassland area declined by 0.4 million ha; 5.3 million ha of agricultural land transitioned to non-agricultural use between 2005 and 2015
U.S. livestock production (4)	Annual use of corn for animal feed dropped by 25.4 million tonnes, which was compensated by increased availability of DDGS and oilseed cake. Efficiency of animal production increased (unit of animal protein produced per unit of feed utilized). Livestock production went up by 4.5 million tonnes of meat.
U.S. crop prices (5)	Corn price shows considerable fluctuation. Highest price levels were observed after the record 2012 drought. Prices in 2015 were $70 above the 2005 level
U.S. trade (6)	Net corn exports rose until the 2012-2013 drought caused a sudden decline, then rebounded. Export volumes in 2015 were similar (-3%) to export levels before introduction of the RFS
Impact on distant economies (7-9)	Brazil corn export increased by 28 million tonnes. Corn production increased by 50 million tonnes, mostly (76%) driven by yield improvement (2.5 tonnes/ha). Harvested area increased by +3.9 million ha (some of this from double cropping)

EVALUATING PROJECTIONS

A comparison of data presented in Chapters 3 to 5 with the statistics from Chapter 8 shows large differences are found in projection of ethanol production, corn use and impacts for corn prices, trade, and indirect land use effects (Table 8.2). The projected growth in ethanol production assumed to estimate impacts in some studies considerably exceeds actual growth. Exception is FAPRI-MU (2009) which provided an accurate estimate. The amount of corn used in biofuel production shows a similar pattern, with high projections for Searchinger *et al*. and Brandão. Projected changes in U.S. corn area were overstated in Brandão (2022). While corn harvested area increased by 2.2 million ha, U.S. crop area did not increase. It declined by nearly 6 million ha. Reductions in cropland area coincided with expansion of permanent grassland and forest area (together increasing by 5 million ha). A decline in U.S. crop area was also calculated by Brandão. Estimations of changes in corn feed use vary. Searchinger *et al*. projected a diversion of 52 million tonnes. Statistics show direct corn use for feed fell 25 million tonnes; this was partly compensated by the feed value of DGGS co-produced with ethanol.

Price developments have been different than projected. Considerable increases were anticipated especially in studies published before 2010 (e.g., Doornbosch en Steenblik, 2007; Searchinger *et al*., 2008). Projections by Searchinger *et al*. (increase of 70%) are close to nominal price changes that were observed when 2005 is compared to 2015, but prices were volatile and statistical analyses question the assumed role of ethanol, placing more emphasis on other macro-economic factors, oil prices, and weather conditions (drought impacting 2012-2013 production).

Brandão calculated a decline of corn exports by 3.4 million tonnes, while Searchinger *et al*. anticipated a drop by 28 mln tonnes. FAPRI-MU, projected a slight increase. In reality, exports did not notably change. A drop during the record drought was corrected soon afterwards (2014). Brazil corn export volume was projected to increase, and this indeed has occurred. But changes in corn area are not the primary driver for increases in agricultural area in Brazil; most observed changes during the period were associated with expansion of oilseeds and grassland. There is no clear link with U.S. biofuel production as U.S. corn exports did not change much during the years ethanol production was expanding and linkages with price fluctuations are also questioned by analyses of historic data. Consequently, it is difficult to attribute land-use change in Brazil - or other crop exporting countries - to U.S. biofuel production.

While crop area in Brazil continued to increase, the rate of deforestation in the years following introduction of U.S. biofuels policies slowed to the lowest level in decades. Formal reports of emissions caused by land conversion in Brazil also show a record low in 2011. While the reliability of formal deforestation statistics is disputed, the analysis of Oladosu *et al*. (2021) showed that causal links between corn exports and ethanol production could not be confirmed in a formal statistical analysis.

Table 8.2 Comparing projections and statistics of major U.S. indicators (statistics are for 2005 - 2015; some parameters in cited studies describe different time periods)

Indicator	Searchinger *et al*. (2008)	FAPRI-MU (2009)	Brandão (2022)	Statistics
Type of analysis	*Economic scenario study*	*General equilibrium models*	*LCA study*	-
Narrative	*Trade and market response*	*Trade and market response*	*Trade and market response*	-
Corn ethanol production (billion litres)	56	39	56	40

Indicator	Searchinger *et al.* (2008)	FAPRI-MU (2009)	Brandão (2022)	Statistics
U.S. corn use in ethanol production (mln tonnes)	138	95	134	92
U.S. additional corn area (mln ha)	2.2	3.9	7.6	2.3
Changes in U.S. cropland (mln ha)	2.2	No data	-3.8	-5.8
U.S. corn price (% change)	+70%	+100%	No data	+75%
U.S. corn trade (mln tonnes)	-28	+0.7	-3.4	-0.7
Brazil corn production (mln tonnes)	No data	No data	Reduction of soybean production	50.2

9. Discussion and conclusion

This report describes two narratives that play a dominant role in models used to assess the impacts of biofuels policies in the U.S. and beyond. The narratives, dubbed '**trade and market response**' and '**internal adjustment response**', represent views that differ strongly in the way biofuel expansion in countries like the U.S. are expected to affect global food production and land use. The models and narratives have been used frequently in studies and reports that evaluate the impact of U.S. biofuel policies after their introduction in the mid 2000's with a main focus on corn starch ethanol. Our analysis focuses on the period 2005 to 2015 in which major increases of corn ethanol output were realised.

Each narrative represents a major line of thinking that explains relations between crop production and crop use and how both respond to the implementation of the increased biofuel targets. Examples of major studies predicting indirect land-use effects caused by expansion of U.S. biofuel production between 2005 and 2015 have been discussed in Chapters 3 to 6. For each study, the analytical framework was identified while results of the anticipated changes in crop output, trade, and land use were presented. Outcomes were compared to statistics in Chapter 8. Chapter 7 presents results of causality checks.

The current chapter evaluates the way the narratives have been successful in predicting impacts of biofuel expansion and presents suggestions for the development of an improved analytical framework.

U.S. BIOETHANOL EXPANSION

Corn-based ethanol production in the U.S. tripled between 2005 and 2015. Many studies had anticipated a larger increase. Crop output and amount of corn diverted to fuel production remained below the levels projected in most studies. One scenario in the Flugge *et al.* analysis (2107), projected corn use levels that were lower under assumed improvements in conversion technology and efficiencies.

The rise in corn output was supported by an expansion of harvested corn area in combination with corn yield improvement and redistribution of corn use among other sectors (for example livestock production). Corn prices did increase but showed strong fluctuation, and the increase was by no means a linear development. Corn price changes have not caused a drop in corn exports or loss of corn export market shares.

Adjustments in corn and livestock production systems allowed the agricultural sector to cover the increased demand (e.g., Szabo 2019). Farmers improved crop management, raised input use, and allocated more time to crop management. New investments in machinery and infrastructure helped to increase efficiency and output levels. Other adjustments include the increase of cropping intensity and replacement of soft grains (wheat and barley) by more productive cereal crops (corn and sorghum).

Although crop output improved and (harvested) corn area went up, historical trends in U.S. land use were not altered. In the 10 years following the introduction of the bioethanol policy, no increase of cropland and agricultural land was observed; loss of crop area continued as it was converted to other uses including housing, grasslands, or forests. This loss coincided with an increase in multiple cropping combined with a reduction of fallow. During the same period, corn area and output in Brazil increased, and export of crops and corn went up. At the same time, the rate of loss of forest area appears to have dropped – at least temporarily.

The fact that Brazil's corn exports went up at the same time that direct corn use for livestock production in the U.S. declined, is cited by some studies as evidence that bioethanol expansion contributes to deforestation. The analysis presented in this report, however, shows that the evidence to link developments in Brazil to expansion of ethanol in the U.S. is weak. The reduction in direct corn use was offset by increasing volumes of DGGS feed, and despite fluctuating corn prices in the U.S., corn exports did not fall except during an intense drought impacting all agricultural commodity prices and exports in the U.S. Importantly, U.S. livestock production did not appear to be affected and continued to rise.

Co-existence of trends does not automatically mean there is a causal relation. As Chapter 8 shows, no formal evidence was found that would confirm causal relations between ethanol production and observed changes in corn prices and U.S. exports. This lack of evidence suggests that some common assumptions and narratives that have been used to assess indirect effects are invalid, or at a minimum, need to be reviewed and improved.

This report did not evaluate impacts of biodiesel production, which will likely be different to those of bioethanol. Increasing biodiesel production is expected to increase availability of crop proteins while the demand for soy and similar vegetable oils will rise.

EVALUATING NARRATIVES

The terminology used throughout this report reflects the terms used in the cited studies. It is noteworthy that some phrases tend to be associated with each narrative. For example, the framing of corn use for ethanol tends to be described as a “diversion from food” in studies aligned with the trade and market response narrative. This description of corn use is not typical in studies aligned to the internal adjustment narrative, which tends to focus more on the capacity for US agriculture to adapt and prepare for future changes in demand based on market data and expectations. A recent GTAP publication also finds that the representation of corn use for ethanol as a diversion is misleading. After over 20 years of consistent improvements in the GTAP modelling system designed to represent biofuels and the US RFS policy, Taheripour *et al.*, (2022) find that US corn is produced for multiple markets including ethanol, HFCS, corn oil, feed, and many other products. Corn is produced as a fungible and transportable commodity that can serve multiple markets simultaneously. Corn is not “diverted” for the RFS any more than corn is diverted for feed or food. Market opportunities, future expectations, and perceived risks drive crop decisions.

Another term often used in studies aligned with trade and market response is “land conversion” which can mean different things but is misleading in that land is not being converted into something else that is not land. In the internal adjustment narrative, land areas with specific land management regimes (crop rotations and cultivation practices) and types of land cover (considering all classes and multiple uses), and terms such as “transition” and “crop rotation” are used. In contrast to ambiguous terms such as “land use, land conversion, and land-use change,” scientific analysis is predicated on precisely defined variables that can be consistently and accurately observed, measured, and verified.

Studies applying the **trade and market response narrative** did more or less correctly project ethanol expansion and increased corn use in biofuel production. Projected increases in food (corn) prices were only observed. Price changes varied over time, suggesting that factors other than biofuel production have a strong or stronger impact. Projected disruption of corn exports has been lacking altogether.

Changes in crop production systems like increased land use intensity and displacement of soft grains have not been projected under the Trade and market response narrative. Responses in Brazil that were predicted have only partly been observed: corn production and exports increased, but the speed of deforestation did not go up. This absence of evidence suggests that there is no strong causal relation between U.S. biofuel expansion after 2005 and land-use change in countries like Brazil. Formal tests for causality so far have not provided proof for this relationship.

Studies applying the **internal adjustment response narrative** also tend to correctly project expansion of corn ethanol output, while the assumption that the crop and livestock production systems would be able to provide additional amounts of corn feedstocks seems to be confirmed. Ethanol production went up without jeopardizing food or feed markets, or corn exports. Adjustments in cropping intensity in the U.S. seem to be in line with projections made by FAO (2018) but replacing soft grains by corn and sorghum has received little attention in literature assessing land-use effects of U.S. biofuel policies.

The lack of food shortages, and of lasting price effects or drops in trade volumes provide an indication that the U.S. food production system has been surprisingly effective in meeting the demands of biofuel production. Indeed, U.S. biofuel production consistently exceeded targets set by the EPA every year until the drought of 2012. No major drops in exports were observed. This means that increases in crop output that were observed in Brazil cannot be attributed to the U.S. biofuel policies. Other factors have been driving crop area expansion and forest loss, which occurred simultaneously. Thus, narratives and model assumptions about such linkages merit revision.

Linking projected drops in U.S. food exports (which did not occur in the period studied) to accelerated loss of forest area and subsequent carbon releases in Brazil (which did occur) is not supported by the evidence reviewed in this study. Yet, assumed emissions from indirect effects of U.S. biofuel production associated with forest loss in other nations, is a major impediment to accessing markets that demand low carbon-intensity fuels. The results of analyses of historic data reported here indicate that Brazilian deforestation should not be associated with U.S. biofuel production via the route of indirect land-use change, at least not in the period between 2005 and 2015. Carbon releases from deforestation in Brazil or elsewhere should be attributed to specific causes identified based on in-situ analyses of enabling and causal factors leading up to the deforestation in each case, rather than assuming a distant relationship with U.S. ethanol production.

LIMITATIONS

Although the outcome of the analysis is straightforward, there are limitations to the data and approach that have been chosen. Throughout this paper, an effort has been made to represent various studies and categorize them in two distinct narratives. The aim was to accurately summarize results in a manner that facilitates contrasts and comparisons but errors and omissions, while unintended, are possible.

Another limitation is that data and statistics are not always accurate. Changes in the way they are collected or evaluated can, in theory, affect the outcome of this study. Such changes have not been analyzed or reported. Further, use of annual statistics may be a source of confusion. The agricultural year in the U.S. is not a calendar year, which makes it sometimes difficult to understand what is meant by projections or statistics. However, most authors and studies cited in our report are well familiar with U.S. agriculture, and it is expected that concepts are used consistently.

The use of national statistics may not adequately identify more local or seasonal fluctuations in corn production or use. The use of quarterly data may help to overcome this limitation, but, as there is only one corn harvest in each 12-month period (whether it be an agricultural or a calendar year), the impact is likely to be very small for the US. The causality analysis presented by Oladosu *et al.* (2021) was done using quarterly statistics.

Another potential source of uncertainty is the source of corn used in animal feed. The source of corn may be whole grain corn or refinery products such as starch, fibers, or gluten. Major changes in the use of whole grains or refinery products could, in theory, affect the outcome of the analysis, as it may affect the energy value of the feed. We found no indication that this may have occurred. Also, it is not expected that (minor) changes in U.S. corn feed composition have affected export of corn or animal products.

Further limitations are related to the fact that changes may have occurred in U.S. livestock feed production during the period of analysis. As the analysis is restricted to corn, major changes in the soybean market have not been included. Soybean is commonly grown in rotation with corn, but changes in the most frequent rotation types may have occurred. We have not found evidence of rotation changes in any of the modelling studies, but that does not mean it did not occur. It is likely that substitution between feed crops and livestock types would evolve over time in models, but we found no indication the authors of the modelling studies found rotation patterns affected major outcomes of their analysis.

IMPROVING APPROACHES TO ASSESS INDIRECT EFFECTS

Both narratives provided frameworks that work relatively well especially early in the production chain (increase in ethanol output, corn use, and corn harvested area). The **trade and market response** narrative correctly projected a rise in corn prices, but price increases have not been constant, and prices reflect many variables omitted from models. For example, the price spike projected by trade and market response narratives that occurred in 2012 is largely attributed to extreme drought conditions in 2012. The **internal adjustment response** narrative studies provide a reliable explanation for the sector's ability to respond to increased crop demand, but some elements (projection of changes in multiple cropping, changes in crop choices) require more attention.

The shortcomings in assessments of biofuel impacts that have been identified in this study – overestimating changes in export volumes and ignoring long-term loss of agricultural area to other sectors –suggest that the estimations of indirect land-use change-related carbon effects need to be adjusted. Long-term effects are either lacking, or weaker than projected; other trends are ignored; and causal relations between domestic (U.S.) developments and changes in distant economies (Brazil etc.) could not be confirmed.

Many authors called for better data and improved approaches to assess indirect land-use change and other indirect effects. Overmars *et al.* (2015) concluded that better data were needed on cropping intensity before these could be incorporated in economic models. Fritsche *et al.* (2010) called for better data on land-use change and trade flows. Models estimating indirect effects should incorporate a land-use change baseline and trend analysis (Kline *et al.*, 2011) while according to Persson (2015), better supply and demand curves are needed, as well as improved models that describe the competition for land by various economic activities.

Some authors called for a more integrated approach that includes elements of both narratives, i.e., evaluate effects on prices and implications for trade volumes as well as implications of agronomic adjustments and innovations in crop management, farm machinery, and logistical infrastructure. Meyfroidt *et al.* (2013) suggest combinations of economic models, statistical studies, local empirical analyses and biophysical accounting methods.

If the ongoing debates about indirect effects are to be settled, an agreed analytical framework and robust and long-term datasets for all variables of concern are required. Studies assessing indirect effects caused by biofuel production and policies need to examine trends in land management, land cover, crop rotations, and agricultural prices and outputs, over periods of time sufficiently long to support representation of historic factors responsible for observed variability prior to, as well as following, the introduction of biofuels.

Effects of biofuels should be estimated on net relative to factors that are often counter-balancing, and with consideration of other variables influencing crop production, prices and land markets. Take for example US Farm Bill subsidies which represent a major source of US farm income and predominantly favour corn and soybean production. While subsidies play a significant role in US planting decisions, they have been omitted from the analyses discussed above. This omission is due to the fact that the subsidies are many, diverse, complex, and their value to farmers varies year-to-year, making them difficult to incorporate in models. However, when one US agricultural subsidy was introduced as a variable in the GTAP model (Taheripour and Tyner, 2014), the subsidy modified GTAP output results for the land-use change acreage estimates associated with biofuel policies by 70% for the USA. The authors state, "We also show that ignoring the reduction of agricultural output subsidies due to higher coarse grain prices induced by biofuels demand leads to very misleading geographical distribution of land use changes."

The analyses in this report find that more back-casting to test model assumptions and elasticity factors (representing relationships among variables) is required to better represent observed changes in cropping intensity, crop rotations, releases of agricultural land, prices, etc.). Given growing experience and two decades of data available since biofuel production began to ramp-up in the US, the effects of biofuel production and policies can be assessed with the support of historic observations, thereby improving accuracy and understanding of how variables, including some that are typically excluded from models, may influence assessment results. When this is done, model simulation results can vary drastically. For example, in 2009, a simple version of GTAP simulated indirect effects of the RFS that were similar in magnitude to those reported by Searchinger. However, the most recent analysis using a refined GTAP model which incorporates adjustments to better reflect historical data and additional variables, found negligible effects of the Renewable Fuel Standard on global markets. Taheripour *et al.*, 2022 report that, "the long-run effects of biofuel production and policy on food prices were negligible... biofuels' contribution to commodity price increases is really no different from fructose corn syrup, increased feed demands, or other market demands."

The examples above illustrate some of the reasons why the **trade and market response** narrative has generated indirect effects that appear exaggerated when compared to statistical analyses of historic data. Models that are designed and calibrated to simulate market responses to a "shock" imposed on a system in equilibrium, are not representative of the reality of the RFS and US biofuel production. Such modelling parameters assume that the demand for biofuels came as a surprise to producers around the world, causing a shock in global markets and therefore, the markets needed to adjust and rebalance. But the RFS policy and targets were announced years in advance of taking effect, and biofuel production in the US began to ramp-up rapidly in 2002-2004, anticipating the new policies, so global markets and US producers had time to prepare for this demand just as they prepare for other known changes in demand based on population trends and preferences.

CONCLUSION

Existing approaches to assess impacts of indirect land-use change are leading to conflicting conclusions. This report identifies two alternative narratives and explains how these approaches are built on assumed causal relations between biofuel production, crop markets and land-use change. An analysis of changes following the introduction of U.S. biofuels policy shows that crucial assumed relations were not observed and that existing frameworks should be improved.

The lack of consistency in the projections based on existing approaches creates confusion for analysts, policymakers, and the general public and frustrates development of coherent and consistent biofuel policies. Existing approaches to assess indirect effects and impacts of land-use change show important shortcomings, and causality for assumed relationships merits review and verification.

Contrary to modelled relationships, statistics showed no link between expansion of U.S. biofuel production between 2005 and 2015 and corn production, corn export, or deforestation in Brazil. Thus, future research should investigate the local conditions and causal factors that enable (or prevent) deforestation. The evidence does not support assertions that US corn use for ethanal is the cause for observed losses of Brazilian forest.

More research is needed to develop and test improved analytical tools to quantify effects of biofuel production including indirect effects, in manners that can be verified. In the meantime, caution should be applied in interpreting estimates of indirect effects and when calculating the corresponding GHG impacts of biofuel production and policies.

An improved methodology is needed to evaluate indirect land use change and associated effects. This requires a more comprehensive scope than one focused on simplified land classes and projections of market and trade adjustments. Flexibility and adaptation within expansive global agricultural systems are apparently far more complex and less predictable than generally assumed or simulated in trade models. The dominant role of trade and market models in biofuel policy evaluation studies should be reconsidered; the flexibility of the U.S. national food production system allows it to adjust more quickly and effectively than generally seems to be assumed. More attention for the way the system responds to shocks is required.

This report identifies ways to improve future assessments of the climate effects of policies that involve land management for bioenergy feedstocks. More specifically, it is recommended to include the following elements in indirect land-use change analysis studies:

- Long-term trends for factors analysed, avoiding two-point comparisons

- Data on harvested areas and multiple cropping
- Crop yields
- Trends in seed, machinery, and labour input
- Full national land balances (accounting for all land in all classes, not just selected crops)
- Trend data that includes the area planted in individual crops, secondary or cover crops, and management over 12-month agricultural years, considering rotations over time (crop matrix) for historic observations (baselines) as well as counter-factual and simulated scenarios
- Explicit long-term evaluation of changes in national and global crop prices and export volumes, and
- Causality checks (complete linkage, weight of evidence, etc.) of assumed relationships.

A more robust and comprehensive approach could provide improved assessments of the effects of policy on land management and land cover, including the corresponding net effects on carbon cycles and climate forcing.

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Appendices

APPENDIX 1 – GLOSSARY

Consequential LCA	estimates how global environmental burdens are affected by the production and use of a product (craddle-to-grave), using marginal data
Attributional LCA	allocates environmental burdens of a process by partitioning them between the life cycles served by the process, using average data
CGE	Computational General Equilibrium
Crop matrix	Matrix of crops cultivated in a given year, identifying area cropped per crop type
Cropped area	Sum of area under annual and permanent crops (including feed crops and temporary grassland but excluding permanent grassland)
Cropping intensity	The ratio between harvested area and cropped area
DDGS	Dried Distiller Grains with Solubles
Double cropping	Two harvests on a given field in a period of 12 months
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GTAP	Global Trade Analysis Project
Harvested area	Area from which a crop is harvested. Not including the area from which, although sown or planted, no harvest could be made
indirect land-use change	Indirect Land-Use Change
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
JRC	Joint Research Centre of the European Commission
LCA	Life-Cycle Assessment
PE	Partial Equilibrium model
RED	Renewable Energy Directive
RFS	Renewable Fuel Standard

IEA Bioenergy

Technology Collaboration Programme