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Biofuels and their by-products: Global economic and environmental implications☆

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ABSTRACT

Recently a number of papers have used general equilibrium models to study the economy-wide and environmental consequences of the first generation of biofuels (FGB). In this paper, we argue that nearly all of these studies have overstated the impacts of FGB on global agricultural and land markets due to the fact that they have ignored the role of biofuel by-products. Feed by-products of FGB, such as dried distillers grains with solubles (DDGS) and oilseed meals (VOBP), are used in the livestock industry as protein and energy sources. Their presence mitigates the price impacts of biofuel production. More importantly, they reduce the demand for cropland and moderate the indirect land use consequences of FGB.

This paper explicitly introduces DDGS and VOBP into a global computational general equilibrium (CGE) model, developed at the Center for Global Trade Analysis at Purdue University, to examine the economic and environmental impacts of regional and international mandate policies designed to stimulate bioenergy production and use. We show that models with and without by-products reveal different portraits of the economic impacts of the US and EU biofuel mandates for the world economy in 2015. While both models demonstrate significant changes in the agricultural production pattern across the world, the model with by-products shows smaller changes in the production of cereal grains and larger changes for oilseeds products in the US and EU, and the reverse for Brazil. Models that omit by-products are found to overstate cropland conversion from US and EU mandates by about 27%.

1. Introduction

The global biofuel industry has been growing rapidly over the past decade. This has resulted in strong growth in the associated by-products. Biofuels from grains, in particular corn, are produced in conjunction with various distillers grains products, mainly dried distillers grains with solubles (DDGS) and wet distillers grains with soluble (WDGS). US DDGS production increased sharply from about 4.5 Mt in 2001 to 11.25 Mt in 2006. Soy and rapeseed meals are joint products obtained from production of vegetable oils from oilseeds. In this paper, we refer to the latter class of by-products as

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Nomenclature

FGB	first generation of biofuels
DDGS	dried distillers grains with solubles
VOBP	vegetable oil by-products
CGE	computational general equilibrium
CDS	condensed distillers solubles
WDGS	wet distillers grains with solubles
CARD	Center for Agricultural and Rural Development
AEZ	agro-ecological zone
GTAP	global trade analysis project
CES	constant elasticity of substitution

VOBP. This paper only concerns first generation biofuels and not possible second generation biofuels that could be produced from cellulose.

Biofuel by-products represent an important component of total industry revenues. For example, each 100 kg of corn used in a typical dry milling ethanol plant generates roughly 40.2 L of ethanol and 32.1 kg of DDGS. Correspondingly, producing 10 L of biodiesel from soybean (rapeseed) generates 38.3 kg (12.3 kg) of soybean (rapeseed) meal. According to our calculations about 16% of a corn based dry milling ethanol plant's revenue comes from DDGS sales. Corresponding shares for typical rapeseed and soybean based biodiesel producers are about 23% and 53%, respectively. These by-products are mainly used as a protein source and their prices are highly correlated with prices of grains and oilseeds.

An important outcome of this joint production process in the biofuel industry is that when biofuel production is encouraged, for example due to government subsidies or positive oil price shocks, the production of these by-products also increases, and, as a result, their prices fall relative to other feed ingredients. This encourages livestock producers to use more biofuel by-products in their production processes. On the other hand, any reduction in the prices of by-products diminishes total revenue and acts as a brake on growth of the biofuel industry. From this perspective, biofuel by-products function as both a shock absorber and a price adjuster.

Another important aspect of biofuel by-products is that they help mitigate the environmental consequences of expansion by the biofuel industry. For example, DDGS substitutes for both corn and soybean meal in livestock rations but mainly for corn. This ultimately reduces the land use consequences of biofuel production and eases the demand for chemical inputs, such as fertilizers and pesticides, in crop production.

The importance of incorporating by-products of biofuel production in economic models is well recognized in several early partial equilibrium analyses of biofuel production. For example, Tokgoz et al. [1] incorporated DDGS as a substitute for corn into the CARD agricultural model at Iowa State University and show that the inclusion of DDGS in the model significantly changes the results. Tyner and Taheripour [2] and Babcock [3] have also incorporated DDGS by-products into their partial equilibrium models to evaluate the economic impacts of biofuel production. By-products from grain milling have previously been incorporated into a CGE framework by Rendleman and Hertel [4] who show that, by ignoring this factor, the benefits to corn producers from the sugar program are greatly overstated. However, to date, this issue has not been tackled by those conducting CGE analysis of biofuels programs, and this has been a serious omission.

Several papers have used CGE models and addressed the economy-wide and environmental consequences of producing biofuels at a large scale (recent examples are: refs. [5–8]). These papers mainly argue that since biofuels are mostly produced from agricultural sources, their effects are largely felt in agricultural markets with major land use and environmental consequences. In this paper, we argue that these earlier studies have significantly overstated the impact of liquid biofuels on agricultural markets due to the fact that they have ignored the role of by-products resulting from the production of biofuels.

In this paper we introduce DDGS and VOBP into a global CGE model, nicknamed GTAP-BIO, developed at the Center for Global Trade Analysis at Purdue University. The GTAP-BIO model is a modified version of the GTAP-E model, originally developed by Burniaux and Truong [9] to incorporate energy into the GTAP framework, and recently modified by McDougall and Golub [10]. Birur et al. [8] have introduced biofuels into this model. They augment the model by adding the possibility for substitutability between biofuels and petroleum products. In a recent work, Hertel et al. [11] have augmented this model with a land use module to accurately depict the global competition for land between land use sectors. The land use module, nicknamed GTAP-AEZ, disaggregates land use into 18 AEZ [12]. AEZs share common climate, precipitation and moisture conditions, and thereby capture the potential for real competition between alternative land uses. They used this model to examine the implications of US and EU biofuel mandate policies for the world economy.

We introduce biofuel by-products into their model and compare our simulation results with their results omitting by-products. This comparison highlights the importance of incorporating biofuel by-products into the economic analysis of policies which are designed to encourage production of biofuels. One of the main obstacles in accomplishing this previously has been the challenge of incorporating biofuels and their by-products into a global, economy-wide data base. Taheripour et al. [13] have explicitly incorporated biofuels production, consumption, and trade into the standard GTAP database. In this paper we introduce by-products into the GTAP-BIO database.

In the standard GTAP framework, there is a one-to-one mapping from commodities to single-product sectors. However, with joint products, the number of commodities is larger than the number of sectors due to the presence of biofuel by-products. This paper divides the global economy into 28 sectors/industries, 30 commodities, and 18 regions comprising the major biofuel producers (including US, EU, and Brazil) as well as non-biofuel producers. It analyzes impacts of implementation of biofuel promotion policies on key economic variables such as land use, production, prices and trade of a wide range of commodities, emphasizing food and agricultural commodities. In particular, this paper examines the global impacts of the US Energy Independence and Security Act of 2007 and the European Union mandates for promoting biofuel production. These mandates are discussed in detail in ref. [11].

2. Data

Taheripour et al. [13] have explicitly introduced three biofuel commodities (including ethanol from food grains, ethanol from sugarcane, and biodiesel from oilseeds) into the GTAP database. In this paper we extend the GTAP-BIO database in several directions to properly trace the link among the biofuel, vegetable oil, food, feed, and livestock industries. We first distinguish between feedstock of the US and EU ethanol industries. In the modified GTAP-BIO database, the US uses corn and EU uses wheat. Accordingly, we split the "other food products" industry into two distinct industries: processed food and processed feed. We also split the vegetable oil sector into two distinct industries: crude vegetable oil and refined vegetable oil. The crude vegetable oil sector uses oilseeds and produces crude vegetable oil (as the main product) and oilseed meal (as the by-product). Unlike the GTAP-BIO database which directly converts oilseeds to biodiesel, we introduce a biodiesel production technology which uses crude vegetable oil and other inputs to produce biodiesel. Finally, we aggregate the modified GTAP-BIO database into 28 industries, 30 commodities, and 18 regions. The revised database covers three distinct livestock industries: dairy farms, ruminants and non-ruminants. Appendix A lists sectors, commodities, and regions covered in the modified aggregated database.

3. Model

The model used in this paper, GTAP-BYP, is a modified version of the GTAP-BIO model introduced earlier. This section explains key equations which have been added to the model. Interested readers may obtain the revised model from the authors upon request.

To introduce by-products into the supply side of the model we revised the zero profit condition of the original model. The original GTAP model and its extensions, including GTAP-BIO, assume each sector only produces one commodity. These models determine the endogenous output level for each and every sector, qo_j, according to the following zero profit condition, expressed in terms of percentage changes in output and input prices:

$$ps_j = \sum_i \theta_i pf_{ij}. \tag{1}$$

Here ps_j, θ_i, and pf_{ij} represent the percentage change in price of output in sector j, the share of input i in total costs of producing commodity j, and the percentage change in price of input i paid by sector j, respectively. The percentage change in derived demands for inputs in these sectors, qf_{ij}, are determined from the following constant elasticity of substitution (CES) equation wherein derived demands depend on sector output (qo_j) and a substitution effect driven by the percentage change in the price of output, relative to the price of the input in question

$$qf_{ij} = qo_j + \sigma_j\left(ps_j - pf_{ij}\right) \tag{2}$$

Here, the parameter σ_j represents the constant elasticity of substitution among inputs in the production function for sector j. Large values of this parameter suggest that input use is quite sensitive to the relative price of the input.

To introduce multiple products into the model we revise the above equations for the grain ethanol and crude vegetable oil industries, each of which produces by-products. To accomplish this we must first introduce two new variables, which are specific to the industry, but generic to the output from that industry. The first refers to the percentage change in the index of activity level in the grain based ethanol and crude vegetable oil industries, qz_i for j = EthanolC and Cveg_Oil. The second is the unit return to activity in each industry, pz_j. The model endogenously determines activity level according to the following zero profit conditions for the grain ethanol and crude vegetable oil industries:

$$pz_j = \sum_i \theta_i pf_{ij} \quad \text{for} \quad j = \text{EthanolC}, \quad \text{Cveg\_Oil}. \tag{3}$$

The change in return to activities in the two industries is simply a composite price index, comprising prices of the main and by-products according to the following equations:

$$pz_j = \sum \Omega_{kj}.ps_{kj} \begin{array}{l}\text{for } j = \text{EthanolC and } k = \text{ethanol1, DDGS,}\\ \text{for } j = \text{Cveg\_oil and } k = \text{Cveg\_Oil1, VOBP.}\end{array} \tag{4}$$

In these equations, Ω_{kj} is the revenue share of the kth product in total revenues of sector j.

Output levels for the industry are a function of activity level and relative prices, where $\sigma_j^T \le 0$ represents the constant elasticity of transformation between the main and by-products in industry j:

$$qo_{kj} = qz_j + \sigma_j^T(pz_j - ps_{kj}) \quad \begin{array}{l}\text{for} \quad j = \text{EthanolC} \quad \text{and} \quad k = \text{ethanol1}, \quad \text{DDGS},\\ \text{for} \quad j = \text{Cveg\_Oil} \quad \text{and} \quad k = \text{Cveg\_Oil}, \quad \text{VOBP}.\end{array} \tag{5}$$

In the case of pure by-products $\sigma_j^T = 0$, and the main and by-products are always produced in a constant proportion.

Finally, we modify the derived demand functions for inputs into the grain based ethanol and crude vegetable oil industries by replacing the indices of outputs with the indices of sector activity levels:

$$qf_{ij} = qz_j + \sigma_j\left(pz_j - pf_{ij}\right) \tag{6}$$

This completes the supply side modifications in the model.

Table 1 – DDGS and corn price correlation coefficients for different time periods.		
Duration	Correlation coefficient	
	Price levels	First differences
1983–2006	0.71	0.70
1983–2000	0.71	0.68
2001–2006	0.73	0.79

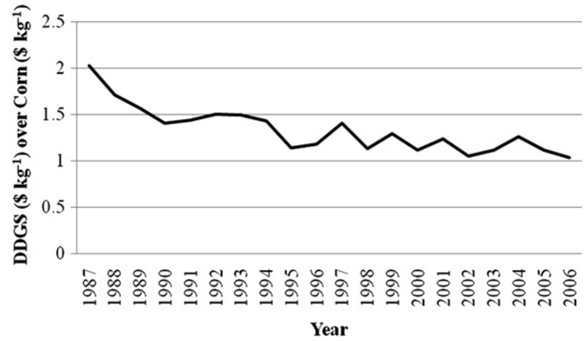


Fig. 2 – The relative price of DDGS and corn (1987–2006).

We now turn to the demand side for the by-products. The use of DDGS in the livestock industry has significantly increased in the US, EU, and many other countries in recent years due to the sharp increase in the grain and oilseed prices. This reflects the fact that DDGS and corn are close substitutes in the livestock industry. Further evidence of this substitution is reported in Table 1 which documents the fact that DDGS and corn prices are highly correlated, and their correlation has strengthened in recent years. Soy and rapeseed meals have always been a major component of animal feeds because they are excellent sources of protein.

To implement the possibility of substitution between by-products and other animal feedstuffs in the demand side of the model, we assume producers, in particular the livestock industries, use DDGS in their production process as a substitute mainly for coarse grains (in particular corn). We also consider VOBP as a substitute for feedstuffs produced by the feed industry. Given these assumptions and following Keeney and Hertel [14] for the general approach to introducing feedstuff substitution in livestock production within the GTAP framework, we define a nested demand structure for feed in the livestock sectors of the model. The demand structure for feed is shown in Fig. 1.

At the lower level of this figure, using a CES nest of the general form shown in Eq. (2), the model combines DDGS and coarse grains to generate a composite input (CDDG). At this level, the model also substitutes VOBP with processed feed to generate another composite input named OBDP. At the higher level the model combines CDDG and OBDP with other feedstuffs used in the livestock industry to generate a composite feed input for this industry. The magnitudes of the elasticities of substitution between coarse grains and DDGS and between processed feed and VOBP are keys to determining the strength of linkage between the prices of DDGS and corn, and the prices of VOBP and processed feed products.

Fig. 2 plots the relative price of DDGS to corn over the 1987–2006 period. From this figure, it is clear that the price of DDGS relative to corn has fallen by nearly 50%. This has provided a strong incentive for livestock producers to use more DDGS in their production process and has also enhanced US exports of DDGS.

Of course, as with any feedstuff, there are limits to the amount of DDGS that can be fed to livestock. Based on these limits, Cooper [15] and Dhuyvetter et al. [16] have reported two estimates of the potential demand for DDGS within the US, which are 42 Mt and 52 Mt, respectively. These numbers are significantly larger than the current US production of DDGS – suggesting that the maximum consumption may not be an issue in the near future. In addition, the potential market overseas is even further from satiation. And US exports of DDGS have increased by more than 50% over this period, rising from 0.8 Mt to 1.25 Mt during the time period: 2001–2006.

We do not have a lot of direct evidence upon which to base our choice of elasticity of substitution between DDGS and coarse gains. However, in our historical simulations, we find that a very large value is required in order to replicate the US price path of DDGS over the 2001–2006 period when ethanol production – and hence the availability of DDGS – was rising sharply, yet DDGS prices were also rising. Allowing for differences in relative ease of use of DDGS in different livestock rations, we used values of 20, 30, and 10 for the elasticities of substitution between coarse grains and DDGS in the dairy farms, other ruminant, and non-ruminant feed structure, respectively. Similarly we apply a value of 50 for the elasticity of substitution between oil meal and traditional processed animal feeds in the three livestock industries

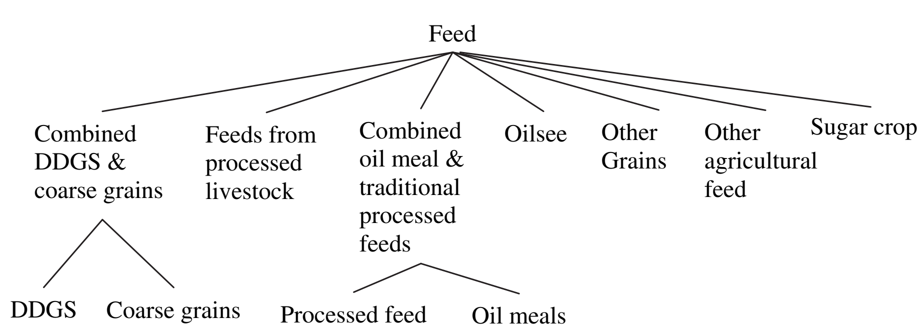


Fig. 1 – Structure of nested demand for feed in livestock industry.

Table 2 – Percentage changes in the outputs of non-energy commodities due to the EU and US 2015 biofuel mandates (base year is 2006).

Agricultural commodities	Without by-products			With by-products		
	US	EU	Brazil	US	EU	Brazil
CrGrains	15.4	−2.4	−1.3	10.8	−8.5	−2.6
OthGrains	−5.7	−1.1	−6.1	−4.4	−0.8	−6.2
Oilseeds	9.1	37.4	17.1	10.4	39.7	16.1
Sugarcane	−0.3	0.5	12.9	−0.3	0.5	13.1
OthAgri	−4.2	−4.3	−4.7	−3.1	−3.9	−4.9
DairyFarms	−0.8	−1.0	0.0	−0.5	−0.8	0.0
Ruminant	−0.9	−1.1	−1.7	−0.5	−0.8	−1.8
NonRuminant	−1.7	−1.2	−1.3	−1.1	−0.9	−1.7
ProcDairy	−0.6	−0.8	−0.5	−0.4	−0.7	−0.5
ProcRum	−0.8	−0.6	−1.9	−0.5	−0.4	−1.9
procNonRum	−0.9	−0.8	−3.3	−0.6	−0.5	−3.6
Forestry	−1.6	−3.4	−2.8	−1.2	−2.7	−2.6
Cveg_Oil1	21.5	106.4	−7.2	21.9	106.1	−4.2
Rveg_Oil	−3.2	−0.5	−6.7	−2.9	−0.4	−4.1
Bev_Sug_Pric	−0.3	−0.4	−1.8	−0.3	−0.3	−1.8
Proc_Food	−0.3	−0.5	−1.1	−0.3	−0.4	−1.0
Proc_Feed	3.7	0.9	−5.7	−5.4	−17.2	−4.7
OthPrimSect	−0.1	−0.1	−0.6	−0.1	−0.1	−0.6
En_Int_Ind	−0.1	0.3	−1.1	−0.1	0.3	−1.1
Oth_Ind_Se	−0.1	−0.1	−0.3	−0.1	0.0	−0.3
DDGS	–	–	–	181.7	413.9	–
VOBP	–	–	–	21.7	105.9	−4.2

feeding structure to replicate the price path of rapeseed meal in the EU over the historical period: 2001–2006. Finally, following Keeney and Hertel [14] we used 0.9 for the elasticity of substitution at the higher level of the feed demand nest. Other important parameters used in this paper are discussed in ref. [11].

4. Alternative scenarios

The goal of this paper is to highlight the importance of incorporating biofuel by-products in the economic and environmental analysis of biofuel production on a global scale. To accomplish this goal we adopt the method developed in Hertel et al. [11]. Those authors have provided an experiment which uses the 2001 database and shocks only those variables that were key in shaping the US and EU biofuel economy over the time period of 2001–2006 to generate a database for 2006. Then they shock the 2006 global economy with US and EU biofuels policies expected to be in place for 2015. In this paper we first replicate their 2006 experiment using our 2001 database, which incorporates DDGS and VOBP, and then we replicate their prospective simulation in the presence of these by-products. In doing the 2006 experiment and the 2015 prospective scenario we only shock the biofuel economy to isolate impacts of biofuel production from other changes which shape the world economy.

5. Simulation results

Here we compare the results from the two prospective scenarios which depict the world economy in 2015 in the presence of the US and EU biofuel mandate policies, both with and without biofuel by-products present in the analysis. In this comparison we highlight the implications for several key economic variables as well as for indirect land use change which has become the most controversial topic surrounding biofuel mandates in the US and the EU.

5.1. *Production*

Table 2 compares percentage changes in the outputs of non-energy commodities during the time period of 2006–2015 for three major biofuel producers (i.e. US, EU and Brazil). The model with by-products estimates that production of DDGS and VOBP grow by 181.7% and 21.7% in the US, respectively (Table 2). Corresponding numbers for EU are 413.9% and 105.9%. These regions mainly produce ethanol from grains and biodiesel from vegetable oil and so, as a result, their DDGS and VOBP outputs grow rapidly with the biofuel mandate policies. For example, the US production of DDGS grows from 11.25 Mt in 2006 to about 31.7 Mt in 2015. A major portion of this by-product is estimated to be used within the US with the rest exported to other regions (about 12.4% of the US DDGS outputs have been exported to other countries such as Canada, EU members, Mexico, and African and Asian countries historically). On the other hand, the EU production of VOBP grows from about 22.5 Mt in 2006 to 46.3 Mt in 2015. The EU production of VOBP will be mainly used within the EU. This huge increment to DDGS and VOBP production significantly alters the global production pattern of agricultural commodities as shown in Table 2.

The models with and without by-products suggest different production impacts of the US and EU biofuel mandates in the biofuel producing regions. For each kilogram of corn converted to ethanol, about 1/3 kg of DDGS is

Table 3 – Percentage changes in the quantities of US exports of grains and oilseeds to selected regains due to 2015 EU and US biofuel mandates (base year is 2006).

Commodity	Without by-products			With by-products		
	EU	Brazil	Middle East & North Africa	EU	Brazil	Middle East & North Africa
Coarse grains	−17.7	−23.2	−21.1	−20.5	−15.8	−15.2
Other grains	29.4	−5.2	−14.8	20.4	−0.2	−9.8
Oilseeds	64.8	−18.1	−25.5	67.4	−11.5	−20.8

Table 4 – Percentage changes in supply prices of non-energy commodities due to 2015 EU and US biofuel mandates (base year is 2006).*

Agricultural commodities	Without by-products			With by-products		
	US	EU	Brazil	US	EU	Brazil
CrGrains	19.8	11.0	9.8	13.0	5.6	7.9
OthGrains	7.2	11.9	8.4	5.0	8.7	6.9
Oilseeds	18.2	31.6	17.2	14.6	26.9	14.8
Sugarcane	11.9	10.7	16.3	8.3	7.8	14.5
OthAgri	9.0	9.5	9.5	6.3	6.9	7.9
DairyFarms	3.8	4.7	6.2	2.3	3.3	5.4
Ruminant	3.6	4.2	5.2	2.2	2.9	4.5
NonRuminant	4.0	3.3	1.7	2.5	2.0	1.6
ProcDairy	1.0	1.2	2.4	0.6	0.8	2.2
ProcRum	1.4	1.3	2.8	0.9	0.8	2.5
procNonRum	1.3	1.2	2.1	0.8	0.7	1.9
Forestry	8.9	14.3	15.7	6.5	10.9	13.2
Cveg_Oil1	29.6	20.6	22.2	27.5	18.7	13.3
Rveg_Oil	7.9	2.0	10.4	7.4	1.8	6.4
Bev_Sug_Pric	0.3	0.6	3.5	0.3	0.4	3.3
Proc_Food	0.4	0.9	2.4	0.4	0.7	2.0
Proc_Feed	2.3	4.3	6.6	1.3	2.8	7.0
OthPrimSect	−0.4	−0.6	0.0	−0.3	−0.5	0.0
En_Int_Ind	−0.4	−0.6	0.2	−0.3	−0.5	0.4
Oth_Ind_Se	−0.4	−0.5	0.3	−0.2	−0.4	0.4
DDGS	–	–	–	2.2	−7.7	–
VOBP	2.6	4.3	6.0	0.2	0.2	9.4

*All price changes are relative to the numeraire, which is a global index of factor prices.

Table 5 – Harvested area changes due to 2015 EU and US biofuel mandates (base year is 2006 and figures are in Mha).

Type of cropland	Without by-product				
	US	EU	Brazil	Others	World
Coarse grains	4.2	−0.5	−0.2	0.7	4.1
Other grains	−1.6	−0.1	−0.3	−0.1	−2.2
Oilseeds	1.6	5.1	2.2	9.4	18.3
Sugar crops	0.0	0.0	0.7	−0.2	0.5
Other agriculture	−2.5	−1.3	−0.6	−0.8	−5.1
Total	1.7	3.2	1.8	9.0	15.6
Type of cropland	With by-product (holding consumption constant)				
	US	EU	Brazil	Others	World
Coarse grains	2.7	−2.2	−0.4	−0.7	−0.6
Other grains	−1.3	0.2	−0.3	−0.4	−1.8
Oilseeds	2.1	5.6	2.1	8.3	18.1
Sugar crops	0.0	0.1	0.7	−0.1	0.6
Other agriculture	−2.2	−1.1	−0.5	−1.0	−4.8
Total	1.2	2.6	1.6	6.1	11.5
Type of cropland	With by-product				
	US	EU	Brazil	Others	World
Coarse grains	2.7	−2.3	−0.4	−0.5	−0.4
Other grains	−1.3	0.2	−0.3	−0.4	−1.9
Oilseeds	2.0	5.6	2.1	8.6	18.4
Sugar crops	0.0	0.1	0.7	−0.1	0.6
Other agriculture	−2.0	−0.9	−0.5	−0.9	−4.3
Total	1.3	2.7	1.6	6.8	12.3

produced, so it is hardly surprising that the model with by-products included predicts about one-third less rise in US coarse grains production (10.8% vs. 15.4%). The difference between these two numbers corresponds to 14.1 Mt of corn, which could be used to produce about 5.5 hm^3 of ethanol. The model with no by-products predicts a 2.4% reduction in coarse grains production in the EU, but the model with by-products predicts 8.5% reduction in this same variable. In the presence of by-products, the EU uses domestic and imported by-products to support its livestock industry (EU has imported about 0.32 Mt of DDGS from the US in 2006), and less feed grains are needed. As a result, the EU does not need to allocate more land to meet the demand for grains used in its livestock industry. Instead, it allocates additional land to produce more oilseeds to support its biodiesel production. As indicated in Table 2, the model with biofuel by-products predicts larger percentage changes in oilseed outputs in both US and EU and a lower change in Brazil.

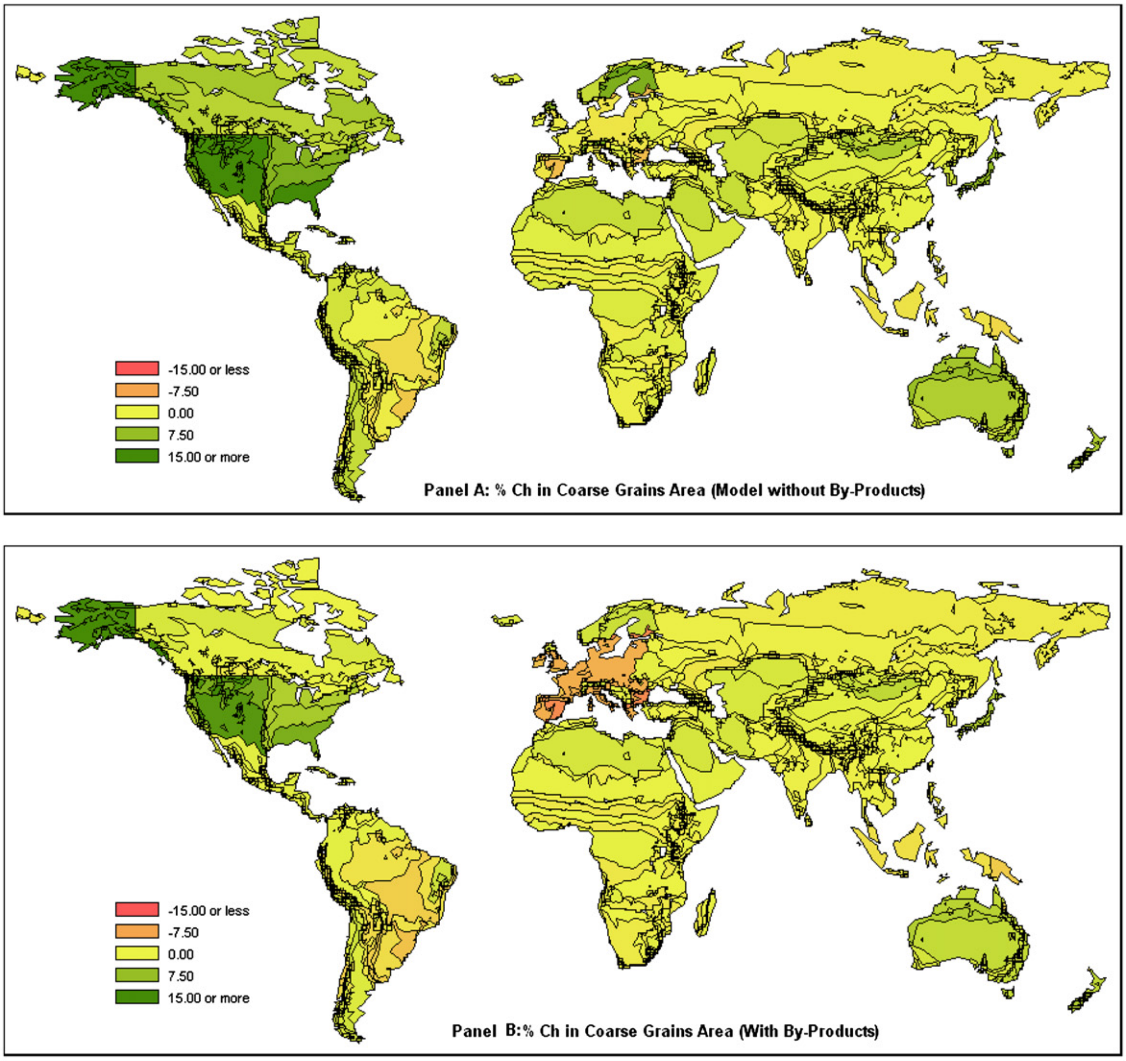
Both the models predict modest declines in the livestock and processed livestock outputs in the US, EU, and Brazil, as higher priced feedstuffs contribute to higher cost livestock products which reduce consumption. But the model with by-products included estimates lesser declines in US and EU livestock production. With these industries contracting less, the Brazilian industry contracts more, as it does not benefit significantly from the lower cost by-products. Both models predict sharp increases in production of crude vegetable oil and moderate reductions in outputs of refined vegetable oil to support sharp increases in biodiesel outputs. There are very small changes in outputs of the food industries (including beverage, sugar, processed rice, and food products) as a consequence of the growth in biofuels production in the US and EU.

5.2. *Trade*

Introducing by-products into the model alters the trade effects of the US–EU mandate policies as well. For example, as shown in Table 3, the model with no by-products estimates that the US exports of coarse grains to EU, Brazil, and Middle East & North Africa (a major importer of DDGS) will drop sharply by −17.7%, −23.3% and −21.1%, respectively in the wake of higher biofuel production. The corresponding figures for the model with by-products are −20.5%, −15.8%, and −15.2%. These figures indicate that EU and Middle & North Africa reduce their coarse grains imports in the presence of by-products, while Brazil imports more coarse grains. The models with and without by-products predict similar growth in US exports of oilseeds to the EU (about two-thirds) as the biodiesel industry in that region expands and absorbs more domestically produced rapeseed. The two models predict sharply different declines in US exports of oilseeds to Brazil and Middle East & North Africa. For example, while the model with no by-products predicts an 18.1% reduction in US exports of oilseeds to Brazil, the alternative model estimates only a 11.5% reduction.

5.3. *Prices*

We now compare the price consequences of introducing by-products into the model. Table 4 compares percentage



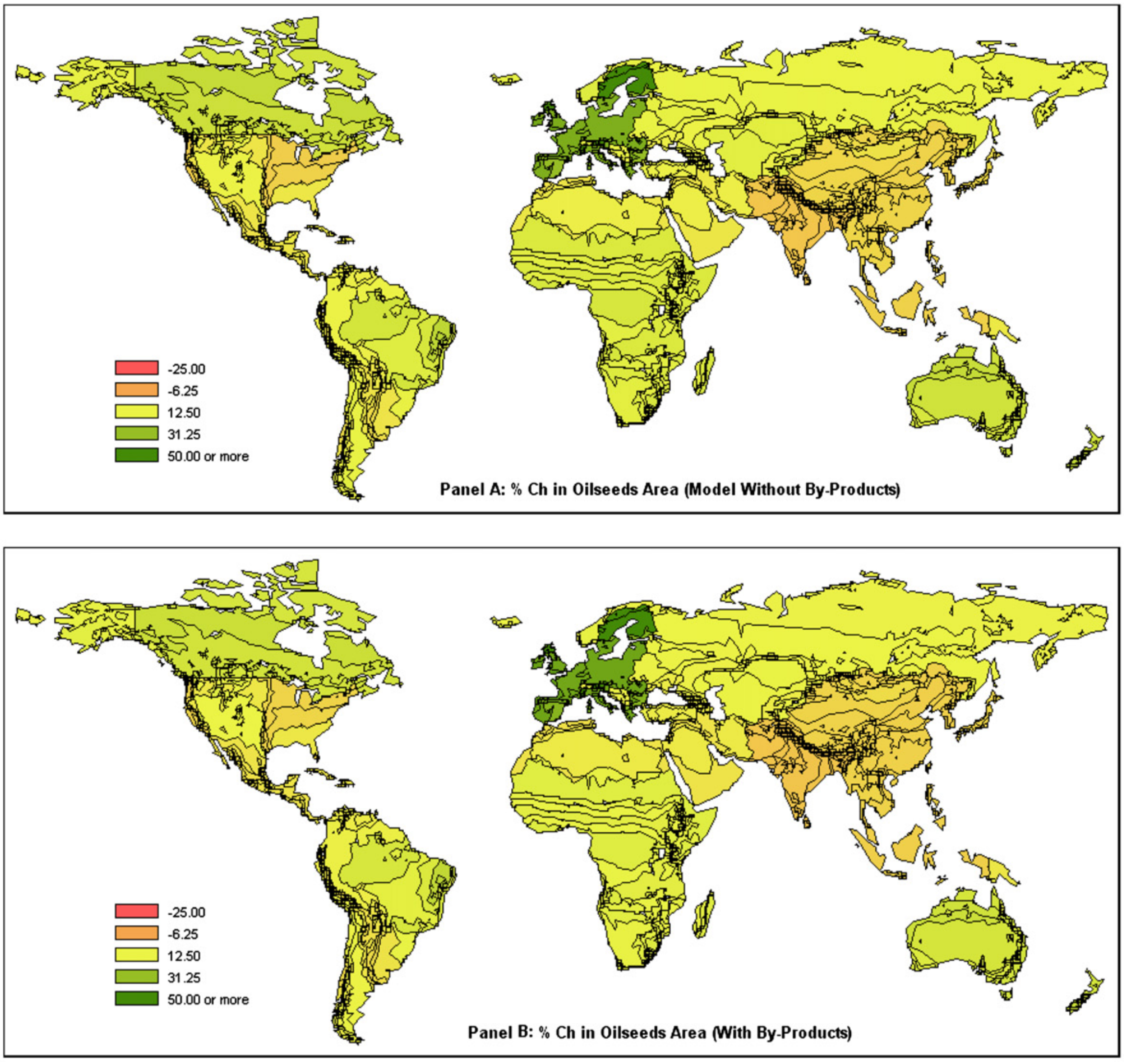
Coarse-grains area change (2006-15)		US	EU	Brazil	Others	World
Panel A: Without by-products	%	11.3	-1.5	-2.0	0.3	1.4
	Mha	4.2	-0.5	-0.2	0.7	4.1
Panel B: Model with by-products	%	7.1	-6.7	-2.9	-0.2	-0.1
	Mha	2.7	-2.3	-0.4	-0.5	-0.4

Fig. 3 – Change in Land Area under Coarse Grains across AEZs (2006–2015).

changes in the prices of non-energy commodities for the two prospective simulations, relative to the numeraire in the model (a global index of factor prices). In general, both models predict sharp increases in the prices of agricultural commodities, while prices increase at significantly lower rates in the presence of by-products. For example, the model with no by-products demonstrates that the price of coarse grains increases sharply in the US, EU, and Brazil by 19.8%, 11.0%, and 9.8%, respectively. The model with by-products presents considerably lower percentage changes of 13.0%, 5.6%, and 7.9% in these countries, respectively. Both models predict sharp increases in the price of the crude vegetable oil in the US, EU and Brazil. The US and EU biofuel mandates have no major impact on the price of VOBP in US, EU, and Brazil. For other commodities, prices grow at slightly lower rates in the presence of by-products compared to the case with no by-product.

5.4. *Land use and land cover*

Introducing by-products in the model also significantly alters the land use consequences of biofuel production within the US, EU, and Brazilian economies, as well as elsewhere (Table 5). To examine the scale of this change, we compare three alternative cases. First, we consider the case with no by-products. Then we introduce by-products into the model, but we hold the consumption of food commodities (including final consumption of all agricultural commodities, beverages, and food products) at the same level as for the case with no by-product.



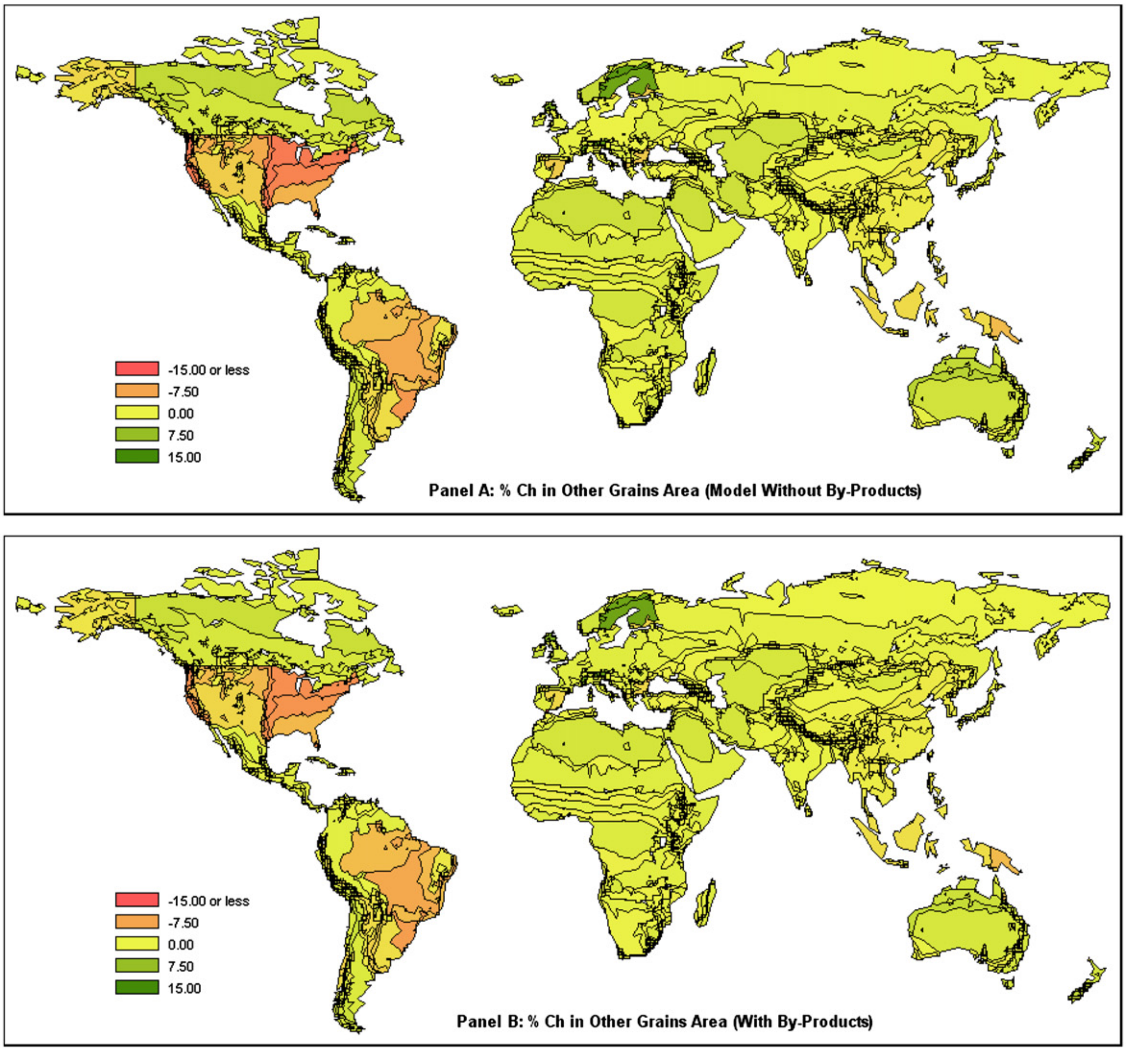
Oilseeds area change (2006-15)		US	EU	Brazil	Others	World
Panel A: Without by-products	%	4.9	35.8	15.2	7.6	9.9
	Mha	1.6	5.1	2.2	9.4	18.3
Panel B: Model with by-products	%	6.1	39.1	14.6	7.0	9.9
	Mha	2.0	5.6	2.1	8.6	18.4

Fig. 4 – Change in Land Area under Oilseeds across AEZs (2006–2015).

The second case provides a partial equilibrium analysis of land use implications of having by-products in the model. Finally, we remove the constraint on food consumption to examine the full effect of introducing by-products on land use changes. The beauty of the intermediate (food consumption exogenous) scenario is that it permits us to isolate the consumption impact of by-products, which has previously been overlooked in the literature.

The top panel of Table 5 indicates that in the absence of by-products the US and EU biofuel mandates increase the demand for cropland by 15.6 Mha. The distribution of changes in cropland across alternative crops indicates that in the absence of by-products, the global demands for land to produce coarse grains and oilseeds increase by 4.1 Mha and 18.3 Mha, respectively. In this case, the global use of land to produce other grains and other agricultural commodities is reduced by 2.2 Mha and 5.1 Mha, respectively. Sugar crop area rises slightly due to the use of imported sugarcane ethanol from Brazil.

In the second case, when we introduce by-products and keep food consumption at the level of the first case, the global rise in cropland demand for land falls to 11.5 Mha. This is mainly due to the reduction in the demand for coarse grains area. In this second simulation, global coarse grains area is essentially unchanged, while the impact of increased ethanol production is largely felt through competing crops. This stems from the fact that increased production of DDGS and oilseed



Other -grains area change (2006-15)		US	EU	Brazil	Others	World
Panel A: Without by-products	%	-7.0	-0.4	-7.3	-0.04	-0.6
	Mha	-1.6	-0.1	-0.3	-0.14	-2.2
Panel B: Model with by-products	%	-5.8	0.6	-7.1	-0.13	-0.5
	Mha	-1.3	0.2	-0.3	-0.39	-1.9

Fig. 5 – Change in Land Area under Other Grains across AEZs (2006–2015).

meals can jointly reduce the demand of livestock industry for corn and offset the increase in the demand of ethanol industry for grains due to the US and EU biofuel mandates.

We now remove the constraint on the demand for food to investigate the full impact of introducing by-products into the model. When we remove the food consumption constraint, the demand for food responds to the presence of by-products in the food system by ending up at a higher level than would be the case in the absence of by-products. This boosts global cropland area by 0.8 Mha, compared to the second scenario, or 12.3 Mha in total. The difference between the demand for land obtained from the first and the third case is about 3.3 Mha. This figure represents the moderation in the global demand for land owing to the presence of by-products in our analysis.

Figs. 3–5 demonstrate global changes in land areas under coarse grains, oilseeds, and other crops due to the US and EU biofuel mandates and compare results of models with and without byproducts.

We now consider the impacts of biofuel mandates on land cover (Table 6). Following [11] we allow cropland to come from either pasture or currently accessible forestlands. The mix of these two types of cover changes will depend on current land cover in the Agro-Ecological Zones in which feedstocks are produced, as well as the change in returns to land in these two competing activities. As with the previous table, Table 6 estimates land cover changes due to the mandates for three sets of model assumptions. In the third panel of this table, which represents the full effect on biofuel

Table 6 – Land cover changes due to 2015 US and UE biofuel mandates (base year is 2006 and figures are in Mha).

Land type	Without by-product				
	US	EU	Brazil	Others	World
Forest	−0.4	−2.6	−0.9	0.1	−3.8
Cropland	1.7	3.2	1.8	9.0	15.6
Pasture land	−1.3	−0.7	−0.9	−9.0	−11.9
Total	0.0	0.0	0.0	0.0	0.0
Land type	With by-product (holding consumption constant)				
	US	EU	Brazil	Others	World
Forest	−0.2	−2.0	−0.9	0.6	−2.5
Cropland	1.2	2.6	1.6	6.1	11.5
Pasture land	−1.0	−0.6	−0.7	−6.7	−9.0
Total	0.0	0.0	0.0	0.0	0.0
Land type	With by-product				
	US	EU	Brazil	Others	World
Forest	−0.3	−2.1	−0.9	0.3	−3.0
Cropland	1.3	2.7	1.6	6.8	12.3
Pasture land	−1.0	−0.6	−0.7	−7.0	−9.3
Total	0.0	0.0	0.0	0.0	0.0

mandates, about 9.3 Mha of pasturelands (75.6% of total cropland change) are converted to crop production due to mandates. Only a quarter of the cropland is expected to be converted from accessible forestlands. Finally, it should be borne in mind that these are all *net changes in land cover*. In practice, pasture land may move into crops and forest land may move primarily into pasture.

6. Conclusions

This paper uses a general equilibrium framework to study the importance of biofuel by-products in the economic analysis of policies which are designed to encourage production of biofuels. This study shows that incorporating biofuel by-products in such analyses considerably alters the results in the face of 2015 international biofuel mandates. While both models demonstrate significant changes in agricultural production pattern across the world, the model with by-products shows smaller changes in the production of cereal grains and larger changes for oilseed products in the US and EU, and the reverse is true for Brazil. In the presence of by-products, mandate-driven price changes are dampened. Finally, we conclude that, the studies that ignore by-products may be misleading in their estimates of land use and land cover changes due to biofuel mandates.

Acknowledgments

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Appendix.

List of industries and commodities.

Industry name	Commodity name	Description	Corresponding name in the GTAP_BIOB
CrGrains	CrGrains	Cereal grains	Gro
OthGrains	OthGrains	Other grains	pdr, wht
Oilseeds	Oilseeds	Oil seeds	Osd
OthAgri	OthAgri	Other agriculture goods	ocr, pfb, v_f
Sugarcane	Sugarcane	Sugar cane and sugar beet	c-b
DairyFarms	DairyFarms	Dairy products	Rmk
CattleRum	CattleRum	Cattle & ruminant meat production	Ctl
NonRum	Non-Rum	Non-ruminant meat production	oap, wol
ProcDairy	ProcDairy	Processed dairy products	Mil
ProcRum	ProcRum	Processed ruminant meat production	Cmt
ProcNonRum	ProcNonRum	Processed non-ruminant meat production	Omt
Forestry	Forestry	Forestry	Frs
Cveg_Oil	Cveg_Oil	Crude vegetable oil	A portion of vol
	VOBP	Oil meals	A portion of vol
Rveg_Oil	Rveg_Oil	Refined vegetable oil	A portion of vol
Bev_Sug_Pri	Bev_Sug_Pri	Beverages, tobacco, sugar, and processed rice	b_t, pcr, sgr
Proc_Food	Proc_Food	Processed food products	A portion of ofd
Proc_Feed	Proc_Feed	Processed animal feed products	A portion of ofd
OthPrimSect	OthPrimSect	Other primary products	fsh, omn
Coal	Coal	Coal	Coa
Oil	Oil	Crude oil	Oil
Gas	Gas	Natural gas	gas, gdt
Oil_Pcts	Oil_Pcts	Petroleum and coal products	p-c
Electricity	Electricity	Electricity	Ely
En_Int_Ind	En_Int_Ind	Energy intensive industries	crpn, i_s, nfm

(*continued on next page*)

Appendix (*continued*)

Industry name	Commodity name	Description	Corresponding name in the GTAP_BIOB
Oth_Ind_Se	Oth_Ind_Se	Other industry and services	crpn, i_s, nfm, atp, cmn, cns, dwe, ele, fmp, isr, lea, lum, mvh, nmm, obs, ofi, ome, omf, osg, otn, otp, ppp, ros, tex, trd, wap, wtp, wtr
EthanolC	Ethanol1	Ethanol produced from grains	
	DDGS	Dried distillers grains with solubles	
Ethanol2	Ethanol2	Ethanol produced from sugarcane	
Biodiesel	Biodiesel	Biodiesel produced from vegetable oil	

Regions and their members.

Region	Description	Corresponding countries in GTAP
USA	United States	Usa
CAN	Canada	Can
BRAZIL	Brazil	Bra
JAPAN	Japan	Jpn
CHIHKG	China and Hong Kong	chn, hkg
INDIA	India	Ind
C_C_Amer	Central and Caribbean Americas	mex, xna, xca, xfa, xcb
S_o_Amer	South and other Americas	col, per, ven, xap, arg, chl, ury, xsm
E_Asia	East Asia	kor, twn, xea
Mala_Indo	Malaysia and Indonesia	ind, mys
R_SE_Asia	Rest of South East Asia	phl, sgp, tha, vnm, xse
R_S_Asia	Rest of South Asia	bgd, lka, xsa
EU27	European Union 27	aut, bel, bgr, cyp, cze, deu, dnk, esp, est, fin, fra, gbr, grc, hun, irl, ita, ltu, lux, lva, mlt, nld, pol, prt, rom, svk, svn, swe
Russia	Russia	Rus
R_Europe	Rest of European countries	che, xef, xer, alb, hrv, xsu, tur
MEAS_NAfr	Middle Eastern and North Africa	xme, mar, tun, xnf
S_S_AFR	Sub Saharan Africa	Bwa, zaf, xsc, mwi, moz, tza, zmb, zwe, xsd, mdg, uga, xss
Oceania	Oceania countries	aus, nzl, xoc

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