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Bioenergy and Global Land Use Change[1]

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Abstract: This is the first paper that estimates the global land use change impact of growth of the bioenergy sector. Applying time-series analytical mechanisms to fuel, biofuel and agricultural commodity prices and production, we estimate the long-rung relationship between energy prices, bioenergy production and the global land use change. Our results suggest that rising energy prices and bioenergy production significantly contribute to the global land use change both through the direct and indirect land use change impact. Globally, the total agricultural area yearly increases by 35578.1 thousand ha due to increasing oil price, and by 12125.1 thousand ha due to increasing biofuel production, which corresponds to 0.73% and 0.25% of the total world-wide agricultural area, respectively. Soya land use change and wheat land use change have the highest elasticities both with respect to oil price and biofuel production. In contrast, non-biomass crops (grassland and rice) have negative land use change elasticities. Region-specific results suggest that South America faces the largest yearly total land use change associated with oil price increase (+10600.7 thousand ha), whereas Asia (+8918.6 thousand ha), South America (+4024.9 thousand ha) and North America (+1311.5 thousand ha) have the largest yearly total land use change associated with increase in biofuel production.

Keywords: Land use change, bioenergy, commodity prices, biofuel support policies.

JEL classification: C14, C22, C51, D58, Q11, Q13, Q42.

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Bioenergy and Global Land Use Change

1 Introduction

During the past decades, several countries around the world have launched extensive biofuel support programs to increase the production of biofuels from agricultural resources. While the positive impact of bioenergy on environment is widely recognised, unintended negative impacts on environment and agricultural sector are less known. However, they are of particular concern with respect to biofuels, which may change, for example, the use of agricultural land. On the one hand, through increased competition for land, the rise of bioenergy sector reduces food production and hence increases food prices (Ciaian and Kancs 2011; Kristoufek et al. 2012a,b; Mallory et al. 2012; de Gorter, Drabik, and Timilsina 2013). On the other hand, increased profitability of biofuel production creates incentives to extend the total agricultural area, e.g. through deforestation (Gardner 2007; de Gorter and Just 2009; FAO 2010; Janda et al. 2012).[5]

The main objective of the present study is to estimate the magnitude of the induced global land use change. In particular, we aim to assess the land use change impact of increasing oil prices which, together with bioenergy support policies, make the production of bioenergy more profitable and hence increase the demand for agricultural land.

Theoretical literature identifies two types of biofuel impacts on land use: a direct land use change (LUC) impact and an indirect land use change impact (Gardner 2007; Kancs 2007; de Gorter and Just 2009; Ciaian and Kancs 2011). The direct impact on LUC captures the substitution in land use between different types of agricultural commodities, i.e. the conversion of agricultural land from food to bioenergy crops. The indirect LUC impact captures expansion of the total agricultural area, implying that new land, which previously was not used for agricultural production (e.g. idle land, forest land), is converted into farmland.

Both types of land use adjustments can be transmitted from energy markets to agricultural markets through an indirect input channel and through a direct biofuel channel (Ciaian and

[5]Ramankutty and Foley (1999) have estimated that the average annual rate of deforestation was about 4.25 MH during the time period of 1850--1990. The annual rate of deforestation has increased to 8.3 MH in 1990s (FAO, 2010).

Kancs 2011). The indirect input channel works through agricultural production costs, whereas the direct biofuel channel works through changes in the demand for agricultural commodities. The relative strengths of the two channels which, among others, depends on the relative importance of energy-based inputs in agricultural production and on the share of biofuel production in the total energy demand, determines the long-run equilibrium on food, energy and bioenergy markets.

The empirical evidence tends to support the theoretical predictions: generally, a positive impact of biofuels on land use change has been found in the literature. The existing literature studying the land use changes applies mainly partial and general equilibrium models (CGE) to simulate the land use implication of biofuels (e.g. Al-Riffai et al. 2010; Andrade de Sa et al. 2010; Blanco et al. 2010; Börjesson and Tufvesson 2011; Diermeier and Schmidt 2012; Havlík et al. 2011; Swinton et al. 2011) (Table 1). Most of these studies find that biofuels have an impact on land use. However, the effects vary significantly between studies. Important sources of variation are scenario considered, parameter assumptions, particularly those that directly or indirectly affect biofuels such as yields and technology. The main disadvantage of the CGE approach is that the simulated effects largely depend on calibrated or arbitrary assumed model parameters and elasticities and may provide unrealistic LUC estimates.

Significantly less studies apply econometric approach which allow to partially address the disadvantage of CGE models (Peng and Liao 2011; Diermeier and Schmidt 2012; Kerr and Olssen 2012; Piroli, Ciaian and Kancs 2012). However, the main shortcomings of these reduced form empirical studies are that they do not straightforwardly provide theoretical basis about the interaction between biofuels and land use. Diermeier and Schmidt (2012) analyse the effects of crude oil and food commodity prices on land use. They estimate VAR models using annual price and land use data for three countries (the U.S., Indonesia and Malaysia) and two products (maize and palm oil). They find Granger causal effects on the area of maize, suggesting that oil price triggers the expansion of the cultivated area and production of maize which, in turn, induces second round effects from maize prices to cereals and wheat. The substitution effect provides evidence of a direct land use change impact.

Kerr and Olssen (2012) estimate the relationships between the New Zealand's rural land use and export prices of agricultural commodities using time-series analytical mechanisms. The estimated long run elasticities suggest a positive relationship between the agricultural land use and the associated commodity prices, but a negative relationship between the agricultural commodity land use and prices for other commodities (Kerr and Olssen, 2012). These results provide evidence of a direct land use change impact.

Peng and Liao (2011) analyse the relationship between the agricultural land use change and farmland protection policy in China using a cointegration analysis. They find strong and positive relationship between the farmland area and farmland protection policy, indirectly providing evidence of a pressure on land use change. In contrast, the estimated effect is weak in the opposite direction (Peng and Liao, 2011).

Piroli, Ciaian and Kancs (2012) analyse the land use change impact of bioenergy support policies in the U.S. They find that energy prices significantly affect land use. The magnitude of the long-run price transmission elasticities with respect to oil price varies between -32 and 18 thousand hectares for individual commodities and between 54 and 68 thousand hectares for the total land per 1 dollar/barrel increases in fuel price, depending on the time horizon considered.

A major limitation of previous econometric studies is that they cover only few countries (usually in Asia or North America) and/or few products. Important bioenergy production regions, such as Europe and South America, have not been studied at all. In addition, none of the existing studies attempt to separately identify the direct land use change impact from the indirect land use change impact. As a result, only limited policy conclusions can be drawn about the global land use change associated with rising energy prices and bioenergy production.

The present paper attempts to fill this gap by estimating the global land use change impact of rising energy prices and bioenergy production. In particular, we estimate the land use change impact for 6 major traded agricultural commodities (maize, wheat, rice, soya, rape and sugar) in 5 continents (Asia, Africa, North America, South America, Europe and Australia). By applying time-series analytical mechanisms to fuel prices, biofuel production and agricultural land use, we attempt to separately identify the direct land use change impact from the indirect land use change impact.

The present paper extends the previous research in two respects. First, this is the first paper that econometrically estimates the global land use change impact of rising energy prices and bioenergy production. In particular, we estimate the LUC impact for 6 major traded agricultural commodities (maize, wheat, rice, soya, rape and sugar) in 5 continents (Asia, Africa, North America, South America, Europe and Australia). Second, by applying time-series analytical mechanisms to fuel prices, biofuel production and agricultural land use, we attempt to separately identify the direct LUC impact from the indirect LUC impact.

The estimated land use change elasticities confirm interdependencies between energy, bioenergy and agricultural markets identified in the theoretical literature (Gardner 2007; de Gorter and Just 2009; Ciaian and Kancs 2011). Our results suggest that rising energy prices and bioenergy support policies contribute significantly to the global land use change. On the one hand, the share of agricultural commodities being used for bioenergy production increases compared to food production. On the other hand, the total cultivated area expands, as the energy prices are rising.

These results have high policy relevance, because a better understanding of the food-energy-environment relationship may allow to increase policy efficiency and to reduce negative/offsetting side effects. For example, increasing food prices may have undesirable social implications, as they affect particularly the poor (Negash and Swinnen 2012). Tapping into land resources currently not or extensively used may have undesirable environmental implications, and may offset the positive environmental effects associated with the production of bioenergy (Searchinger et al 2008). In order to avoid such undesirable side effects, policy makers need to understand the food-energy-environment relationship in the context of expanding bioenergy production. Our study provides such insights by estimating the sign and magnitude of the global land use change.

2 Theoretical hypotheses

According to theoretical analysis of Gardner (2007), de Gorter and Just (2009), Ciaian and Kancs (2011), Drabik (2011), and Mallory et al. (2012) the interaction between food, fuel and bioenergy markets are transmitted through two channels: an indirect input channel and a direct biofuel channel. Fuel affects land use through the indirect input channel by altering farm production costs on the agricultural market, whereas the direct biofuel channel interacts through biofuels' demand for agricultural commodities on the agricultural markets.

Total land use change (indirect LUC). Fuel price affects agricultural production costs and hence the profitability of land through the indirect input channel by translating an increase in fuel price into a decrease in land demand. Due to higher input (fuel) costs, the production and hence land use decreases, because agricultural land and fuel are imperfect substitutes. The direct biofuel channel has an opposite (positive) effect on the total land demand. Higher fuel price stimulates biofuel demand, leading to an upward adjustment of agricultural prices, thus improving land profitability. Higher agricultural land demand stimulates conversion of idle and forest land into agricultural land (Table 2).

The overall effect depends on the relative strength of the two channels. If biofuels play an important role in agricultural markets, then the direct output (biofuel) channel will offset the indirect input channel resulting in higher land use. Otherwise, the total land use will decline. Hence, the output channel will likely be stronger than the input channel, in the period of biofuel expansion.

Land use substitution between commodities (direct LUC). As a result of biofuel expansion, also land use substitution between agricultural commodities takes place. The indirect input channel has the same impact on both biomass (i.e. commodities used for biofuel production) and food commodities (i.e. commodities not used for biofuel production): an increase in fuel price causes higher production costs, leading to lower land cultivation of both commodities. The exact impact on LUC depends on the relative fuel intensity of agricultural commodities. As a result of an increase in fuel price, fuel intensive commodities will reduce land demand relatively more than fuel extensive commodities.

The direct biofuel channel will affect biomass and food commodities differently (Table 2). The demand for biomass in the biofuel production due to higher fuel prices will stimulate land cultivation. On the other hand, the food commodity's land demand will decline due to rising biofuel price, as farmers will substitute production to the more profitable biomass. Depending on the substitutability between agricultural outputs and energy intensity of inputs, the overall effect will be different for the two types of commodities. For biomass, the LUC depends on the relative strengths of the two channels (as in the case of indirect LUC). For the food commodity, both channels work in the same direction: due to higher input (fuel) costs, the average costs increase, the relative profitability decreases, and hence the land use decreases.

3 Empirical approach

3.1 Estimation issues

The theoretical hypotheses derived in section 2 suggest that energy, bioenergy and agricultural markets are mutually interdependent. Energy prices affect agricultural markets through agricultural production costs, and through biomass demand for biofuel production. Reversely, agricultural markets affect energy markets through agricultural fuel demand and biofuel supply. The volatile growing bioenergy sector and fluctuations in the oil price suggests that this relationship may be non-linear, because the relative strength of the two channels (indirect input and direct biofuel) depends among others on the size of bioenergy sector and fuel price.

The estimation of non-linear interdependencies among interdependent time series in presence of mutually cointegrated variables is subject to several estimation issues. First, in standard regression models, by placing particular variables on the right hand side, the endogeneity of explanatory variables sharply violates the exogeneity assumption in presence of interdependent time series (Lütkepohl and Krätzig 2004). Second, non-linearities in the relationship between energy, bioenergy and agricultural markets suggest that the standard linear regression model would not be able to capture these non-linearities.

3.2 Econometric specification

In the context of multiple cointegrated times series, the problem of endogeneity can be circumvented by specifying a Vector Auto-Regressive (VAR) model on a system of variables, because no such conditional factorisation is made a priori in VAR models. Instead, all variables can be tested for exogeneity subsequently, and can be restricted to be exogenous based on the test results. Given these advantages, we follow the general approach in the literature to analyse the causality between endogenous variables and specify a VAR model (Lütkepohl and Krätzig 2004).

In a first step, the stationarity of time series is determined. Unit root tests are accompanied by stationarity tests to establish whether the time series are stationary. The results of the Augmented Dickey Fuller unit root test (ADF), the Phillips Perron unit root test (PP) and the Dickey Fuller Generalised Least Square test (DFGLS) are compared to the results of Kwiatkowski--Phillips--

Schmidt--Shin stationarity test (KPSS test) to ensure the robustness of the test results. The number of lags of a dependent variable is determined by the Akaike Information Criterion (AIC).

According to Perron (1989), one of the weaknesses of the conventional unit root tests is that they are sensitive to structural changes. Therefore, we use the Zivot and Andrews (1992) procedure to test for unit roots with potential structural breaks. It is important to test for structural breaks, because biofuels impact on land use may change over time. For example, important structural changes may take place when comparing the periods before and after biofuel expansion. The null hypothesis of the Zivot and Andrews Unit Root (ZAUR) test is a unit root with a structural break. The ZAUR test endogenously identifies the most likely break point. Whereas the level shift specification allows for a structural change in the level, the regime shift specification allows for a structural change in both the level and the slope of the trend.

In a second step, the Johansen and Juselius's (1990) cointegration method is specified to test for cointegration. As usual, the number of cointegrating vectors is determined by the lambda max test and the trace test. We followed the Pantula principle to determine whether a time trend and a constant term should be included in the estimable model. According to Gregory and Hansen (1996), there might be a structural break affecting the power of conventional cointegration tests. Gregory and Hansen propose a cointegration test, which accommodates a single endogenous break in the underlying cointegrating relationship, with the null hypothesis of no cointegration versus the alternative hypothesis that there is cointegration in the presence of a structural break. For this reason, we use both Johansen cointegration test and Gregory Hansen test for cointegration with a break in the cointegrating relationship. The advantage of this test is the ability to treat the issue of a break (which can be determined endogenously, unknown break) and cointegration altogether.

This test procedure offers four different estimable models: a level shift model (1), a level shift with trend model (2), a regime shift model (3) and a regime and trend shift model (4).

Model 1: Cointegration with level shift:

$$Y_t = \mu_1 + \mu_2 D_t + \alpha_1 X_t + \varepsilon_t \qquad (1)$$

Model 2: Cointegration with level shift and trend:

$$Y_t = \mu_1 + \mu_2 D_t + \beta_{1t} + \alpha_1 X_t + \varepsilon_t \tag{2}$$

Model 3: Cointegration with regime shift:

$$Y_t = \mu_1 + \mu_2 D_t + \alpha_1 X_t + \alpha_2 X_t D_t + \varepsilon_t \tag{3}$$

Model 4: Cointegration with regime and trend shift:

$$Y_t = \mu_1 + \mu_2 D_t + \beta_{1t} + \beta_{2t} D_t + \alpha_1 X_t + \alpha_2 X_t D_t + \varepsilon_t \tag{4}$$

where Y is the dependent variable (land use), X contains all independent variables (oil price, biofuel production), t is time subscript, ε is the error term and D_t is a dummy variable: $D_t = 0$ if $t \leq$ time of break and 1 otherwise.

4 Data and results

4.1 Data and variable construction

Our data set consists of annual observations for the harvested areas of maize, wheat, rice, rapeseed, sugar crops, soybean, arable land, grassland and total land, world crude oil price and world biofuel production over the period 1961-2009. Data for the harvested areas are extracted from the FAO database, crude oil price data are extracted from World Bank database, and world biofuel production data are obtained from the Instituto do Açúcar e do Alcool in Brazil for the years 1961-1974, and the Earth Policy Institute for the years 1975-2010 (see Figures Figure 1 and Figure 2). Data for the construction of macroeconomic variables are taken from the Global Trade Analysis Project (GTAP) v.8 database. As usual, we apply a logarithmic transformation to all variables.

4.2 Specification tests

Testing for the stationarity of the series, we find that according to the ADF, PP, DFGLS and KPSS tests almost all variables are non-stationary in levels at the 5% significance level, but stationary in first differences, suggesting that our time series are integrated of order 1, that is I(1).[6] Several variables are not stationary in first differences, they are integrated of order 2. These

[6]Some series are integrated of a different order, but we have sufficient evidence that the majority of the series are

variables are the total land use in all regions, grassland in the world, in Asia and in Southern America, and arable land in Southern America. This implies that for these variables the estimated land use effects will represent the impact of oil price and biofuel production on the growth rate change, but not in the level change as in the case of other variables.

4.3 Estimated elasticities of land use change impact

On the basis of the cointegration test results, we proceed with the empirical analysis in those cases, where a long-run cointegrating relationship could be established. The estimated coefficients in the cointegrating equation allow us to derive long-run land use change elasticities with respect to the oil price and with respect to the world biofuel production. We estimate both the oil price and the biofuel production effects in order to ensure the robustness of the results. Overall, a stronger impact is expect between the biofuel production and land use, because likely the indirect input channel is smaller for bioenergy production than for oil price (Ciaian and Kancs 2011).

The results are reported in Table 3 and Table 5 for the world as an aggregate and world regions, respectively. Given that all variables are in natural logarithms, the coefficient estimates can be directly interpreted as elasticities. The left panel reports the long-run LUC elasticities with respect to the oil price, and the right panel with respect to the biofuel production. For example, a maize land elasticity with respect to the oil price implies that a one percent increase in the oil price would induce an increase of 0.022 percent in maize land, whereas the maize land elasticity with respect to the biofuel production implies that a one percent increase in the biofuel production would lead to an increase of 0.026 percent in maize land (Table 3).

According to Table 3, almost all estimated elasticities are positive, and all of them are significant. Only for grassland, we estimate negative land use change elasticity. In line with the underlying conceptual framework, the area of grassland (food-crops in Table 2) is more likely to decline compared to the area of arable land (biomass-crops in Table 2), if oil price and biofuel production would increase. Our estimates confirm the theoretical hypothesis saying that, due to raising energy prices, grassland will be substituted for arable land, the estimated oil price elasticities are -0.002 and 0.001, respectively. The total land use increases with both oil price and

stationary in first differences I(1).

biofuel production (elasticities 0.003 and 0.002, respectively).

Regarding the specific agricultural commodities, the highest elasticity of land use change with respect to the oil price is estimated for rape land (0.085), following by soya land (0.072), sugar land (0.043), maize land (0.022), and wheat land (0.022) (Table 3). The smallest elasticity is estimated for rice land (0.015), which confirms the theoretical hypothesis saying that, due to raising energy prices, the area of rice land (food-crops in Table 2) is more likely to decline than the area of other agricultural commodities (biomass-crops in Table 2), because rice is being used predominantly for the production of food. The estimated low elasticity of rice land use change with respect to the production of biofuels (0.029) confirms that the cultivated area of rice is least likely to expand due to increasing oil price or biofuel production. The highest elasticity of land use change with respect to the production of biofuels is estimated for soya land (0.260). These results are in line with our expectations and theoretical predictions, as biomass from soya is an important input in global biofuel production.

According to the estimation results for world regions (Table 5), the majority of the estimated elasticities are positive and significant. In line with estimates for the aggregated world, the highest land use change elasticities are estimated for rape land and soya land: 1.120 for oil price → rape land in Asia, 1.101 for oil price → rape land in North America, 0.877 for oil price → rape land in South America, 0.865 for oil price → soya land in Europe. We estimate the highest elasticities for rape and soya land also with respect to biofuel production: 1.349 for biofuel production → soya land in South America, 1.283 for biofuel production → rape land in Australia, 1.132 for biofuel production → soya land in Europe and 0.450 for biofuel production → rape land in South America (Table 5). These results are in line with our theoretical hypothesis, as both commodities (soya and rape) are extensively used in the production of biofuels.

The largest negative elasticity is estimated for rice land use change (which is a non-bioenergy crop) in Australia: -1.647 with respect to the oil price and -2.036 with respect to biofuel production. We also find a decrease in the area under rice due to an increase in biofuel production for South America (-0.114), North America (-0.090), Europe (-0.061) and Africa (-0.04). These results confirm our theoretical hypothesis, that the agricultural land used for non-bioenergy crops is being substituted for cultivating bioenergy crops.

The largest increase in the total agricultural area due to an increasing biofuel production is estimated for Asia (LUC elasticity with respect to bioenergy production 0.006), followed by South America (0.004), and North America (0.002). These results can be explained by large unexploited non-agricultural land reserves and on-going deforestation in these regions (FAO 2010). In contrast, the total land use change elasticity for Europe is not significantly different from zero, which can be explained by the fact that there are very limited resources of non-agricultural land which can be converted into agricultural land.

4.4 Estimated area of land use change impact

Based on the estimated long-run land use change elasticities, we calculate marginal and yearly average changes in the cultivated area for each commodity and for the total agricultural area. The results in thousand hectares are reported in Table 4 and Table 6 for the world as an aggregate and world regions, respectively. Column 2 reports the estimated marginal land use changes with respect to oil price, and column 3 with respect to biofuel production. For example, one percent increase in the oil price induces an increase in maize land by 3523.3 thousand hectares (Table 4). Column 4 reports the estimated yearly average land use changes with respect to the oil price, column 5 - with respect to biofuel production. The figures reported in columns 4 and 5 are calculated based on the LUC elasticities in columns 2 and 3 and the observed average yearly increase in oil price and biofuel production over the last ten years.

As expected, the largest total LUC with respect to the crude oil price is estimated for the aggregated world, suggesting that 15600.5 thousand hectares of the total increase in the world-wide agricultural area can be attributed to an increase in the crude oil price by one percent (Table 4). The second largest increase in the total agricultural area due to an increase in crude oil price is estimated for South America (+4648.2 thousand ha, Table 6), which in the literature is often attributed to deforestation (FAO 2010). Similarly, the largest total LUC with respect to biofuel production is estimated for the aggregated world, suggesting that 8365.3 thousand hectares of the total increase in the world-wide agricultural area can be attributed to an increase in biofuel production by one percent (Table 4). The impact of increasing bioenergy production on the total LUC is also significant in Asia (+6153.1 thousand ha, Table 6) and South America (+2776.9 thousand ha, Table 6). In none of the other world regions the total land use change exceeds one million hectares, confirming low elasticities of the total agricultural land supply found in the literature (Piroli, Ciaian and Kancs 2012).

According to column 4 in Table 4, the largest average yearly LUC associated with an increase in oil price is estimated for the total agricultural land (+35578.1 thousand ha), followed by soya land (+15694.4 thousand ha), wheat land (+11312.6 thousand ha), maize land (+8035.2 thousand ha), and rape land (+5977.4 thousand ha). The largest average yearly land use change associated with an increase in biofuel production is estimated for soya land (+35853.6 thousand ha) and wheat land (+16241.5 thousand ha).

The estimates reported in Table 6 suggest that the largest land use substitution between different agricultural commodities takes place in North America, South America and Asia, followed by Europe. These results confirm our expectations, as these four regions are the largest producers of biofuels in the world, and are in line with previous finding in the literature on land use change impacts of bioenergy.

5 Conclusions

The present paper extends the previous research in two respects. First, this is the first paper that econometrically estimates the *global* land use change impact associated with rising energy prices and bioenergy production. In particular, we estimate the LUC impact for 6 major traded agricultural commodities (maize, wheat, rice, soya, rape and sugar) in 5 continents (Asia, Africa, North America, South America, Europe and Australia). Second, by applying time-series analytical mechanisms to fuel prices, biofuel production and agricultural land use, we attempt to separately identify the direct land use change impact from the indirect land use change impact.

Our estimates confirm both types of biofuel impacts on land use identified in the theoretical literature: a direct land use change impact and an indirect land use change impact. First, we find that the total agricultural area is expanding due to increasing biofuel production, which confirms the indirect land use change impact. Globally, the total agricultural area yearly increases by 35578.1 thousand ha due to increasing oil price, and by 12125.1 thousand ha due to increasing biofuel production. This area corresponds to 0.73% and 0.25% of the total world-wide agricultural area, respectively.

Second, we find a direct impact on land use change through land use substitution between different types of agricultural commodities, i.e. the conversion of agricultural land from food to bioenergy crops. Depending on the type of agricultural land use, one percent increase in the oil price causes a global LUC between -6929.4 thousand ha (grassland) and +6881.8 thousand ha (soya land). The elasticity of the global LUC with respect to biofuel production is estimated between -8130.9 thousand ha (grassland) and +24735.8 thousand ha (soya land). These commodity-specific results suggest that soya land use change and wheat land use change have the highest elasticities both with respect to oil price and with respect to biofuel production. In contrast, grassland and rice land have negative LUC elasticities. These results are in line with the theoretical expectations, which suggest that non-biomass commodities will be substituted for biomass commodities, when biofuel production becomes more profitable.

Assuming the observed average yearly increase in oil price and biofuel production over the last ten years, region specific-results suggest that South America faces the largest yearly total land use change associated with oil price increase (+10600.7 thousand ha), whereas Asia (+8918.6 thousand ha), South America (+4025.0 thousand ha) and North America (+1311.5 thousand ha) have the largest yearly total land use change associated with increasing biofuel production.

The estimated land use change elasticities confirm the theoretical hypothesis of interdependencies between energy, bioenergy and agricultural markets. Our results imply that rising energy prices and bioenergy support policies contribute significantly to the global land use change. On the one hand, the share of agricultural commodities being used for bioenergy production increases compared to food production. On the other hand, the total cultivated area expands, as energy prices and bioenergy production are rising.

These results have high policy relevance, because a better understanding of the food-energy-environment relationship will allow to increase policy efficiency and to reduce negative/offsetting side effects. Tapping into land resources currently not or extensively used may have undesirable environmental implications, and may offset the positive environmental effects associated with the production of bioenergy. Our study provides such insights by providing quantitative estimates of land use change in the main world bioenergy production regions and at the global level.

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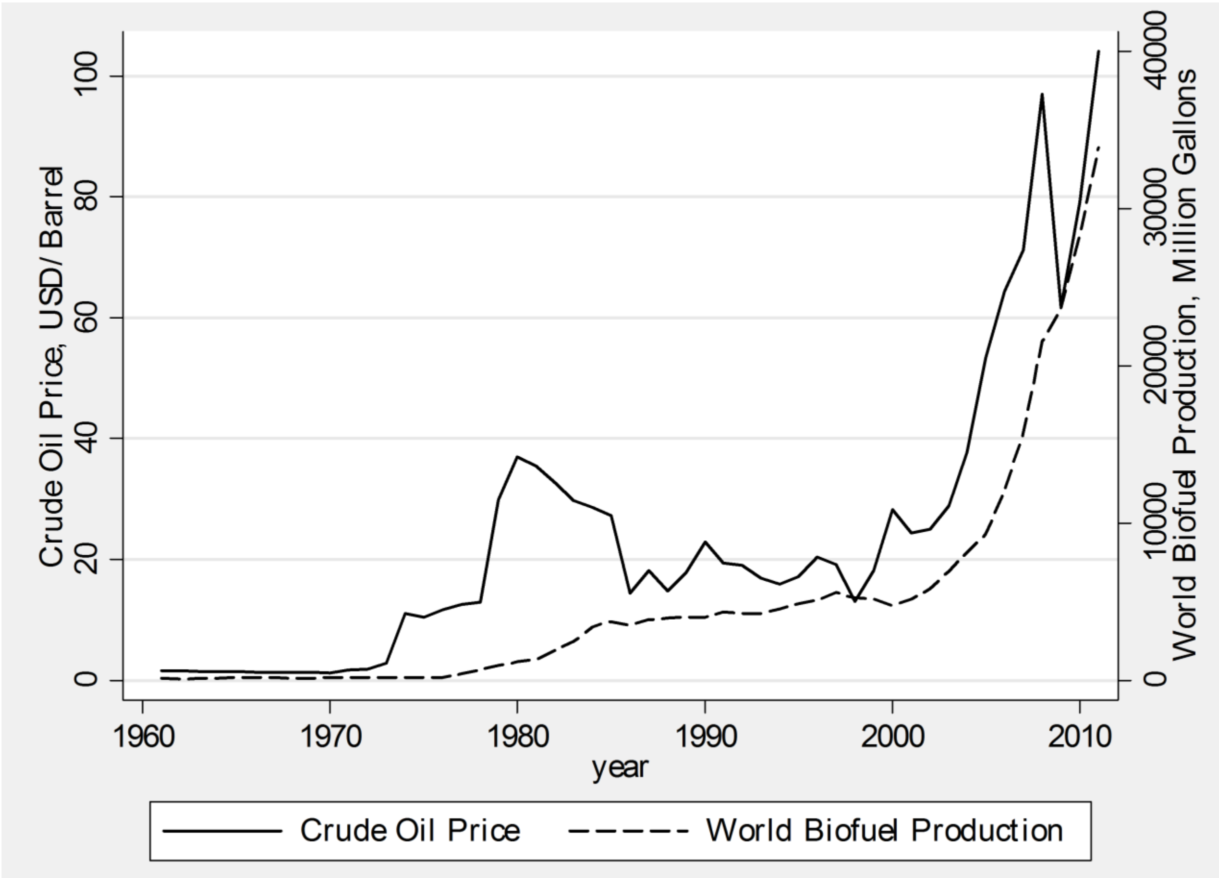
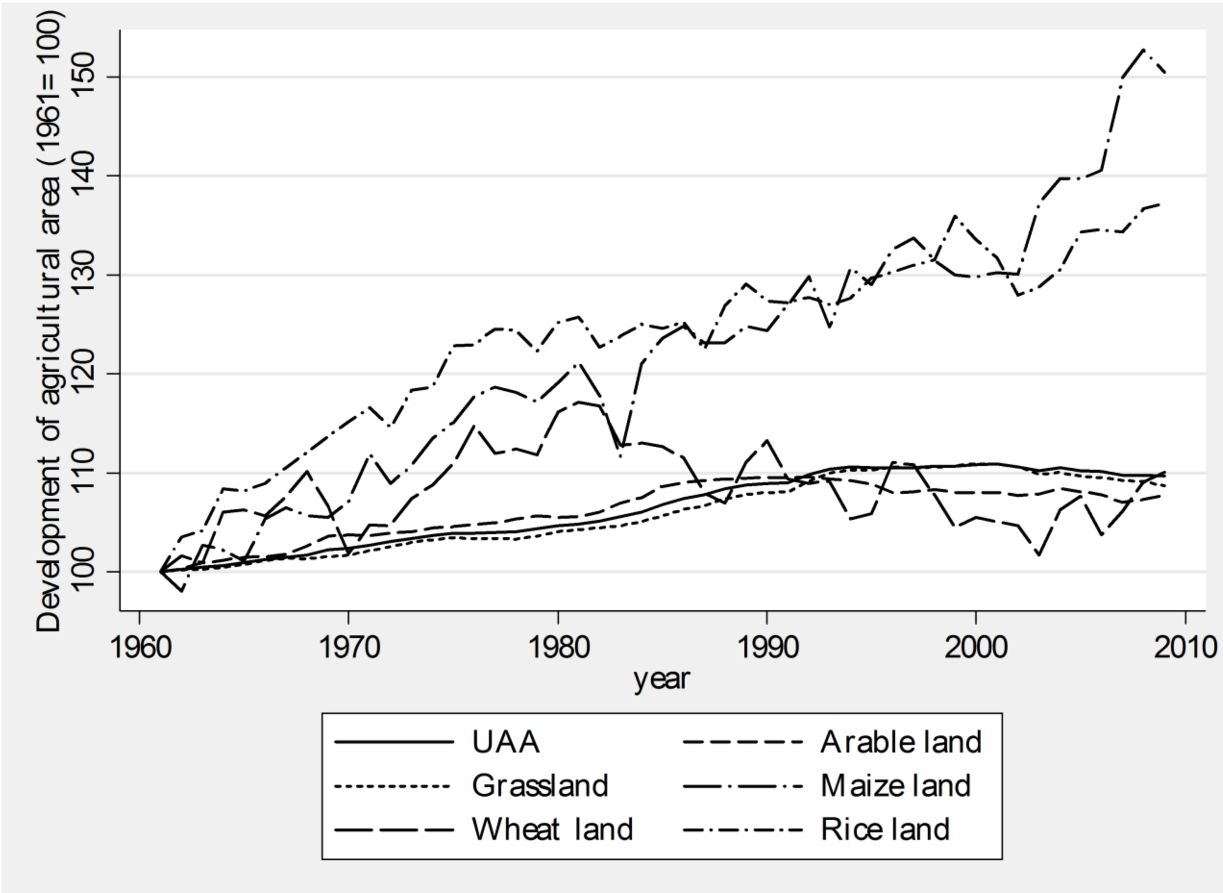
Figure 1: Development of global biofuel production and oil price



Sources: World Bank, Instituto do Açúcar e do Alcool in Brazil Earth Policy Institute

Figure 2: Development of global agricultural land use



Source: FAO

Table 1: Summary literature review

Paper	Method	Aim	Results
Al-Riffai et al. (2010)	General equilibrium model (MIRAGE)	EU biofuels policies; iLUC effects	ILUC effects through deforestation outside the EU (especially in Brazil)
Andrade de Sa et al. (2010)	Partial equilibrium model	Ethanol production; land use; deforestation	Impact of ethanol production on forest conversion is ambiguous
Börjesson and Tufvesson (2011)	Life cycle approach	Biofuels in Northern Europe; land use	Direct LUC has a significant impact on GHG balances
Carriquiry et al. (2010)	Partial equilibrium model (CARD)	Biofuel sector in the European Union; land use	One additional Mtoe of wheat ethanol (rapeseed oil biodiesel) use in the EU expands world land area used in agricultural production by 366,000 (352,000) ha
Piroli, Ciaian and Kancs (2012)	Cointegration approach	Impact of oil price on U.S. land use	Direct and indirect LUC significant. Increase of total agricultural land between 54 and 68 thousand ha per 1 dollar/barrel increase in fuel price
Diermeier and Schmidt (2012)	Cointegration approach	Prices of input factors for biofuel production; areas and quantities of food commodities	Positive effects of commodity prices on land use; no evidence for direct land competition between different biomass-crops
Edwards et al. (2010)	Overview of the models (AGLINK-COSIMO, CARD, IMPACT, G-TAP, LEI-TAP, CAPRI)	ILUC effects	In biodiesel scenario and EU ethanol scenario, most of the LUC effects occur outside the EU; for U.S. ethanol scenarios, most of the ILUC effects are outside the U.S.
Elobeid, Carriquiry and Fabiosa (2011)	General equilibrium model (FAPRI)	Global biofuel expansion; Brazilian land usage	Sugar cane expansion in Brazil takes place at the expenses of other crops or pastures
Harvey and Pilgrim (2011)	Review of studies	Demand for energy; competition for land	Competition for land driven by energy and food demand
Havlík et al. (2011)	Partial equilibrium model (GLOBIOM)	ILUC effects, deforestation, expanding biofuel acreage	The impact of the first generation biofuels is positive on ILUC; the second generation biofuels would lead to a negative ILUC
Hellmann and Verburg (2010)	Combination of the G-TAP model with IMAGE	EU biofuel directive; European land use; biodiversity	The expected indirect effects of the directive on European land use are much greater than its direct effects
Kauffman and Hayes (2011)	Optimization problem of a social planner	Biofuel production; Environmental costs; land constraint	Land constraint makes the trade-off between energy and GHG less obvious than what is implied by conventional life cycle assessments
Kerr and Olssen	Cointegration approach	Land use in New Zealand	Change in land share for all productive uses increases as commodity prices increase

(2012)			
Kim et al. (2010)	General equilibrium model	U.S. and EU biofuel mandates; land use; forestry stocks	Biofuel policies may cause an additional 23-26 million hectares of forestland losses globally
Kim and Dale (2011)	Annual percentage changes and correlation tests	Biofuel production in the U.S.; changes in croplands	Biofuel production in the U.S. up through the end of 2007 has not induced ILUC
Lahl (2010)	Regional model approach	Biofuels; land use changes	Biofuel sector causes a relatively small part of the entire ILUC effect; LUC is mainly caused locally
Peng and Liao (2011)	Cointegration approach	Land use in China	Policies have significant impact on LUC
Searchinger et al. (2008)	Life cycle model (GREET)	U.S. corn ethanol; cropland; sugar crops	56 billion liters of ethanol, would bring 10.8 mil. ha of land into cultivation; much of the ILUC occurs in Latin America, Southeast Asia, and the U.S.
Swinton et al. (2011)	Theoretical model	Biofuels; U.S. non-crop marginal land	The 57 billion liter target of cellulosic ethanol consumption would require at least 21 million hectares of marginal land
Taheripour et al. (2008)	General equilibrium model (G-TAP)	Biofuels; mandates; LUC	Biofuels cause changes in agricultural production worldwide; smaller (larger) changes in the production of cereal grains (oilseed products) in the U.S. and EU, the reverse for Brazil
Tyner et al. (2010)	General equilibrium model (G-TAP)	US corn ethanol; land use changes	24.4% of the LUC occurs in the U.S., 75.6% in the ROW; forest reduction accounts for 32.5% of the change and pasture 67.5%
Wise et al.	Recursive, dynamic market equilibrium model (GCAM)	Biofuels targets; land use around the world	Land devoted to food crops and bioenergy crops may increase by about 10% by 2050, with concurrent decreases in forests and pastures

Table 2:Theoretical hypothesis of predicted LUC impact

Channel	Total land use	Biomass-crops land use	Food-crops land use
Indirect input	(-)	(-)	(-)
Direct biofuel	(+)	(+)	(-)
Net effect	(-) / (+)	(-) / (+)	(-)

Notes: (-) and (+) denote a decrease and an increase in land use, respectively.

Table 3: Estimated **global** long-run land use change **elasticities** with respect to the oil price and biofuel production

	Oil price				Biofuel production			
	Elasticity		Model	Break	Elasticity		Model	Break
Maize-land	0.022	***	2	LT 1979	0.026	**	2	LT 1980
Wheat-land	0.022	***	1(2)	L 1996	0.051	**	4	RT 1983
Rice-land	0.015	***	2	LT 1967	0.029	**	1	L 1968
Soya-land	0.072	***	2	LT 1986	0.260	***	-	-
Rape-land	0.085	*	4	RT 1998	0.031	*	2	LT 2001
Sugar-land	0.043	***	2(1)	LT 2000	0.072	***	1(2)	L 1971
Arable-land	0.001	***	4(3)	RT 1986	-		-	-
Grassland	-0.002	**	3	R 1994	-0.002	***	3	R 1994
Total land	0.003	**	4	RT 1992	0.002	***	2	T 1993

Notes: ***, **, * denote significance at 0.01, 0.05 and 0.10 level, respectively. Models 1, 2, 3 and 4 correspond to the four different models specified: the level shift model (1), the level shift with trend model (2), the regime shift model (3) and the regime and trend shift model (4). Break reports the Zivot and Andrews (1992) Unit Root test results, identify the most probable period and type of a structural break: LT-level trend, L-level, RT-regime trend, R-regime, T-trend. The estimated models contain also dummy variables (to capture macro-economic, technological and demographic developments), which are suppressed for convenience.

Table 4: Estimated area of **global** long-run **land use change** caused by changes in the oil price and biofuel production

	Elasticity of LUC, ha		Total area of LUC, ha	
	Oil price	Biofuels	Oil price	Biofuels
Maize-land	3523.3	4113.2	8035.2	5961.9
Wheat-land	4960.4	11205.2	11312.6	16241.5
Rice-land	2370.7	4570.3	5406.7	6624.5
Soya-land	6881.8	24735.8	15694.4	35853.6
Rape-land	2621.0	963.7	5977.4	1396.8
Sugar-land	1212.9	2012.1	2766.1	2916.5
Arable-land	1445.2	-	3295.8	-
Grassland	-6929.4	-8130.9	-15803.1	-11785.4
Total land	15600.5	8365.3	35578.1	12125.1

Notes: LUC - land use change. The estimated elasticity of land use change in thousand hectares (columns 2 and 3) is calculated based on the elasticities reported in Table 3, and the average land use over the last ten years. The estimated total area of land use change in thousand hectares (columns 4 and 5) is calculated based on the LUC elasticities in columns 2 and 3 and the observed average yearly increase in oil price and biofuel production over the last ten years.

Table 5: Estimated long-run land use change **elasticities** with respect to the oil price and biofuel production: **world regions**

	Oil price				Biofuel production			
	Elasticity		Model	Break	Elasticity		Model	Break
Asia								
Maize-land	0.014	*	2	LT 1984	0.040	**	2	LT 1980
Wheat-land	-		-	-	-0.015	***	3	R 1984
Rice-land	0.011	***	2	LT 1967	0.001		2	LT 1967
Soya-land	-0.081	***	2	LT 1967	0.262	***	4(3)	RT 1986
Rape-land	1.120	***	1(2)	L 1987	0.065	***	3	R 1989
Sugar-land	0.137	***	2(2)	L 1986	-		-	-
Arable-land	-0.018	***	3	R 1983	0.024	***	1(2)	L 2001
Grassland	-0.005	*	3	R 1988	-0.003	***	3	R 1988
Total land	0.001		1	L 1989	0.006	***	2	LT 1988
Europe								
Maize-land	0.026	***	1(2)	L 1968	0.021	***	1(2)	L 1968
Wheat-land	0.016	***	3(4)	R 1978	0.011	**	3(4)	R 1974
Rice-land	-0.067	***	2	LT 1969	-0.061	***	2	LT 1986
Soya-land	0.865	***	1(2)	L 1978	1.132	***	1(2)	L 1978
Rape-land	0.007	***	4	RT 1988	0.395	***	1	-
Sugar-land	0.250	***	3	R 1984	0.260	***	1	-
Arable-land	-		-	-	0.004	***	4(3)	RT 1985
Grassland	-0.022	***	1	L 1988	-0.007	**	2	LT 1988
Total land	0.001		1	L 1987	0.000		1	L 1987
Africa								
Maize-land	-		-	-	-		-	-
Wheat-land	0.007	*	4	RT 1977	0.064	***	1	L 1978
Rice-land	0.130	***	1	L 1989	-0.040	***	2	LT 1998
Soya-land	0.138	***	2	LT 1987	0.230	***	1	L 1987
Rape-land	-		-	-	-		-	-
Sugar-land	0.123	***	1	-	0.175	***	1	L 1968
Arable-land	-		-	-	0.119	***	4	RT 1988
Grassland	0.012	***	3	R 1989	0.011	**	3	R 1989
Total land	0.001		1	L 1993	0.001		1	L 1993
North America								
Maize-land	0.070	***	2	LT 1981	0.051	***	1	L 1981
Wheat-land	-0.041	***	3	R 1999	0.120	***	2	LT 1972
Rice-land	0.113	***	3	R 1992	-0.090	**	2	LT 1976
Soya-land	0.018		4	RT 1983	-0.051		4	RT 1985
Rape-land	1.101	***	1	L 1987	0.382	***	1	L 1967
Sugar-land	-0.099	***	2	LT 1972	0.017	*	2	LT 2001
Arable-land	-		-	-	-		-	-
Grassland	0.007	***	4	RT 1981	-0.006	***	1	L 1970
Total land	0.002	**	1	L 1989	0.002	*	2	LT 1984
South America								
Maize-land	0.027	**	4	RT 1984	0.026	***	1	L 1967
Wheat-land	0.035	*	1	L 1990	-0.035	***	3	R 1988
Rice-land	-0.059	***	3	R 1991	-0.114	***	3	R 1977
Soya-land	0.441	***	2	LT 1968	1.349	***	2	LT 1970
Rape-land	0.877	***	3(4)	R 2000	0.450	**	3	R 1980
Sugar-land	-		-	-	0.211	***	4	RT 1992
Arable-land	-0.005		1	L 1969	-0.005		4	RT 1969

Grassland	0.006	**	4	RT 1996	0.005	***	4	RT 1987
Total land	0.007	**	4	RT 1995	0.004	**	4	RT 1996
Australia								
Maize-land	-0.016	***	4	LT 1987	0.112	**	2	L 1997
Wheat-land	-		-	-	-		-	-
Rice-land	-1.647	***	3	R 1994	-2.036	***	3	LT 1994
Soya-land	0.429	***	2	RT 1970	0.423	**	2	RT 1970
Rape-land	0.654	***	2	L 1968	1.283	***	4	L 1975
Sugar-land	-		-	-	-0.071	***	2	LT 1976
Arable-land	0.057	***	1(2)	LT 1995	0.016	***	1(2)	L 1967
Grassland	-0.074	***	3	RT 1984	-		-	-
Total land	0.000		2	L 1990	0.000		2	LT 1967

Notes: ***, **, * denote significance at 0.01, 0.05 and 0.10 level, respectively. Models 1, 2, 3 and 4 correspond to the four different models specified: the level shift model (1), the level shift with trend model (2), the regime shift model (3) and the regime and trend shift model (4). Break reports the Zivot and Andrews (1992) Unit Root test results, identify the most probable period and type of a structural break: LT-level trend, L-level, RT-regime trend, R-regime, T-trend.

Table 6: Estimated area of long-run **land use change** caused by changes in the oil price and biofuel production: **world regions**

	Elasticity of LUC, ha		Total area of LUC, ha	
	Oil price	Biofuels	Oil price	Biofuels
Asia				
Maize-land	10.2	29.3	23.3	42.5
Wheat-land	-	-1071.4	-	-1552.9
Rice-land	1484.4	134.9	3385.4	195.5
Soya-land	-1635.7	5288.6	-3730.4	7665.7
Rape-land	15140.8	873.3	34529.9	1265.8
Sugar-land	1453.0	-	3313.8	-
Arable-land	-7127.0	9465.2	-16253.7	13719.5
Grassland	-3130.4	-1623.2	-7139.2	-2352.7
Total land	1027.7	6153.1	2343.7	8918.6
Europe				
Maize-land	103.8	83.1	236.8	120.5
Wheat-land	275.3	190.5	627.9	276.1
Rice-land	-27.7	-25.3	-63.3	-36.7
Soya-land	158.2	207.1	360.8	300.1
Rape-land	28.5	1606.3	64.9	2328.3
Sugar-land	331.2	344.2	755.3	498.9
Arable-land	-	290.1	-	420.5
Grassland	-1272.9	-409.2	-2902.9	-593.1
Total land	71.6	53.2	163.4	77.2
Africa				
Maize-land	-	-	-	-
Wheat-land	66.7	590.2	152.1	855.5
Rice-land	1162.5	-355.0	2651.2	-514.6
Soya-land	175.5	292.5	400.3	424.0
Rape-land	-	-	-	-
Sugar-land	210.5	300.0	480.0	434.8
Arable-land	-	26581.6	-	38529.0
Grassland	11218.0	10158.6	25583.6	14724.5
Total land	586.6	586.6	1337.8	850.3
North America				
Maize-land	2391.9	1735.6	5455.0	2515.7
Wheat-land	-1237.6	3667.1	-2822.5	5315.3
Rice-land	135.1	-107.2	308.0	-155.3
Soya-land	548.1	-1547.3	1249.9	-2242.8
Rape-land	7482.7	2595.2	17065.0	3761.7
Sugar-land	-81.5	13.9	-185.8	20.2
Arable-land	-	-	-	-
Grassland	1841.8	-1544.9	4200.3	-2239.3
Total land	729.6	904.8	1664.0	1311.5
South America				
Maize-land	24.1	22.5	55.0	32.7
Wheat-land	312.8	-312.7	713.3	-453.2
Rice-land	-319.1	-616.5	-727.7	-893.6
Soya-land	18348.8	56116.2	41845.9	81338.3
Rape-land	111.5	57.3	254.2	83.0
Sugar-land	-	2203.4	-	3193.8

Arable-land	-737.5	-677.4	-1682.0	-981.9
Grassland	3167.6	2819.4	7224.0	4086.6
Total land	4648.2	2776.9	10600.7	4025.0
Australia				
Maize-land	-1.3	8.9	-2.9	12.9
Wheat-land	-	-	-	-
Rice-land	-16.6	-20.5	-37.8	-29.7
Soya-land	10.1	9.9	22.9	14.4
Rape-land	1022.0	2005.1	2330.7	2906.3
Sugar-land	-	-28.0	-	-40.6
Arable-land	2584.0	742.8	5893.0	1076.7
Grassland	-28408.8	-	-64788.6	-
Total land	34.7	87.5	79.2	126.8

Notes: The estimated elasticity of land use change in thousand hectares (columns 2 and 3) is calculated based on the elasticities reported in Table 5, and the average land use over the last ten years. The estimated total area of land use change in thousand hectares (columns 4 and 5) is calculated based on the LUC elasticities in columns 2 and 3 and the observed average yearly increase in oil price and biofuel production over the last ten years.