Bioenergy and Global Land Use Change[*]

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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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1 Introduction

During the past decades, several countries around the world have launched extensive biofuel programs to support the production of biofuels from agricultural resources. While the positive impact on environment is widely recognised, unintended negative impacts on land use and undesirable side effects of structural changes in agricultural production, are less known. However, they are of particular concern with respect to biofuels, which particularly influence the land-use change. 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). On the other hand, increased profitability of biofuel production creates incentives to extend the total agricultural area e.g. through deforestation (FAO 2010).[1]

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. Our study makes two contributions to the existing literature. First, this is the first paper that estimates the global land use change impact of rising energy prices and bioenergy production. 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.

Indeed, theoretical literature identifies two types of biofuel impacts on land use: a direct land use change 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 land use change 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 land use change impact captures expansion of the total agricultural area, implying that new land, which previously was not used for agricultural production (such as idle land, forest land), is converted into farmland.

Both types of land use adjustments can be transmitted through an indirect input channel and through a direct output channel (Ciaian and Kancs 2011). The indirect input channel works through agricultural production costs, whereas the direct output channel works through changes in the demand for agricultural commodities (which can also be used for biofuel production). 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. 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

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[1] 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).

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 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 empirical 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 extends the previous research in two respects. First, this is the first paper that estimates 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). 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.

The estimated land use change elasticities confirm interdependencies between energy, bioenergy and agricultural markets identified in 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 allows to increase policy efficiency and to reduce negative/offsetting side effects. 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 with respect to the sign and magnitude of land use change.

2 Theoretical hypothesis

2.1 Conceptual framework[2]

In order to identify the key relationships between food, energy and bioenergy markets, we adopt a simple conceptual framework. Compared to other theoretical models in the literature (Gardner 2007; de Gorter and Just 2009), the main advantage of this approach is that it explicitly allows to identify the two key transmission channels of price and quantity signals between the food, energy and bioenergy markets: a direct output channel and an indirect input channel.[3][4]

Building on the theoretical models of Gardner (2007); de Gorter and Just (2009); Ciaian and Kancs (2011), we model five mutually interdependent markets: agricultural, biofuel, fossil fuel, by-product, and farm input. Agricultural farms can substitute their outputs between biomass and food according to a constant returns to scale production function of two substitutable inputs: fuel and land. Biomass output can be supplied either to the food or to the biofuel market, whereas food commodity can be supplied solely to the food market. Biofuel sector uses biomass to produce biofuel and by-product (waste-product). The aggregate fuel supply is a sum of biofuel production and fossil fuel production.

Price signals between food, energy and bioenergy markets are transmitted through two channels: an indirect input channel and a direct biofuel channel. The indirect input channel affects farm production costs on the agricultural market, whereas the direct biofuel channel interacts through biofuels' demand for agricultural commodities on the agricultural markets.

2.2 Land use change impact

Total land use change. 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 (see Table 1).

According to the underlying conceptual framework, 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.

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[2] See Appendix for a formal description of the theoretical model.

[3] The term 'input' refers to inputs used in the agricultural production process, e.g. fuel, land, seeds, fertilisers.

[4] We use the term 'channel' to describe the mechanism of adjustments in prices, production, land use, etc.

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.

Table 1: Theoretical hypothesis of predicted land use change impact

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

Notes: (−) denotes a decrease in land use, (+) denotes an increase in land use.

Land use substitution between commodities. 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 and food commodities: an increase in fuel price causes higher production costs, leading to lower land cultivation of both commodities. The exact impact on land use change 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 (see Table 1). 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 land use change depends on the relative strengths of the two channels (as in the case of indirect land use change). 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 model detailed in section 2 suggests 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 rapidly growing bioenergy sector suggests that this relationship may be non-linear, because the relative strength of the two channels (indirect input and direct biofuel) depends on the size of bioenergy sector.

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, besides the food-energy-bioenergy market linkages identified in the theoretical model, confounding factors may affect the three markets and change the responsiveness of price transmission between them. For example, agricultural and energy markets depend on macro-economic developments, such as GDP growth, population growth, etc. A favourable macro-economic development may induce upward adjustments in both energy and agricultural markets through stimulating production and hence causing land use changes and fuel price rise. These structural adjustments may confound the estimations, causing in the above example an upward bias of the estimated land use change impact.

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 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 very 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. In addition, the level shift specification allows for a structural change in the level, whereas the regime shift specification allows for a structural change in both the level and the slope of the trend.

Johansen and Juselius's (1990) cointegration method is used as a first test for cointegration. 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.

The outlined 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:

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

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.

In order to account for structural factors potentially confounding the estimations, we extend the standard VAR to a “structural equilibrium framework”, by including a number of macro-economic, demographic and policy control variables in the regressions. The inclusion of these structural variables allows us to take into account the key structural effects that otherwise would bias the results (Piroli, Ciaian and Kancs 2012).

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 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 1 and 2). As usual, we apply a logarithmic transformation to all variables.

4.2 Specification tests

Testing for the stationarity of time series, we find that at the 5% significance level the ADF, PP, DFGLS and KPSS tests indicate that almost all variables are non-stationary in levels, but stationary in first differences, suggesting that our time series are integrated of order 1, that is I(1).[5] Several variables are not stationary in first differences, they are integrated of order 2. These variables are the total land in all regions, grassland in the world, in Asia and in Southern America, 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 and 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 can 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 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.

The results are reported in Tables 2 and 4 for the world as an aggregate and world regions, respectively. Given that all variables are in logarithms, the coefficient estimates can be directly interpreted as elasticities. The left panel reports the long-run land use change elasticities with respect to the oil price, 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 (first cell in Table 2).

According to Table 2, almost all estimated elasticities are positive, and all of them are significant. Only for grassland, we estimate a negative land use change elasticity with respect to the oil price. In line with the underlying conceptual framework, the area of grassland (food-crops in Table 1) is more likely to decline compared to the area of arable land (biomass-crops in Table 1), 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 elasticities are -0.002 and 0.001, respectively. An increasing production of bioenergy expands the area of grassland, however, with a lower elasticity than it expands the total utilised agricultural area (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) (see Table 2). The smallest elasticity is estimated for rice land (0.015), which confirms the theoretical hypothesis saying that, due to raising

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[5] Some series are integrated of a different order, but we have sufficient evidence that the majority of the series are stationary in first differences I(1).

energy prices, the area of rice land (food-crops in Table 1) is more likely to decline than the area of other agricultural commodities (biomass-crops in Table 1), because rice is not being used for the production of biofuels. 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 4), 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 (see Table 4). 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 (both significant at 1% level). 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 (-0.040). 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 (land use change 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 ongoing 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 Tables 3 and 5. Column 2 reports the estimated marginal land use changes with respect to oil price, 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 (3.5 million hectares) (first numeric cell in Table 3). 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 land use change 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 land use change 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 (last row in Table 3). 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 5), which in the literature is often attributed to deforestation (FAO 2010). Similarly, the largest total land use change 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 3). The impact of increasing bioenergy production on the total land use change is also significant in Asia (+6153.1 thousand ha, Table 5) and South America (+2776.9 thousand ha, Table 5). 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 3, the largest average yearly land use change 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 5 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. Searchinger et al (2008) use a worldwide model to analyse the land use change impact of ethanol increase in the US. They estimate that ethanol increase of 56 billion litres brings 10.8 million hectares of additional land into cultivation worldwide: 2.8 million hectares in Brazil, 2.3 million hectares in China and India, and 2.2 million hectares in the US.

5 Conclusions

The present paper extends the previous research in two respects. First, this is the first paper that estimates the *global* land use change impact associated with 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). 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: a direct land use change impact and an indirect land use change impact, which have been identified in the theoretical literature.

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 also 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 land use change between -6929.4 thousand ha (grassland) and +6881.8 thousand ha (soya land). The elasticity of the global land use change 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 land use change 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 strong 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 would allows to increase policy efficiency and to reduce negative/offsetting side effects.

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Appendix: Theoretical model

The present model builds on Gardner (2007); de Gorter and Just (2009); Ciaian Kancs (2011). We introduce two important extensions. First, we assume two agricultural commodities: one producing biomass and one producing food.[6] Second, we consider the transmission of prices also through the input channel. Both extensions are important for estimating the total land use change impact.

The economy consists of vertically integrated agricultural, bioenergy, fossil energy, waste-product (by-product), and input markets (Figure 3). The representative farm produces biomass and/or food using constant returns to scale production functions of two substitutable inputs: energy and land. We assume fixed Leontief production technology for biomass transformation into bioenergy and waste-product. Further, we assume a downward sloping demand for food and waste-product, and an upward sloping supply curve for land. The non-renewable energy (i.e. other than bioenergy) supply is given by an upward sloping supply curve, the aggregate energy supply is a sum of bioenergy and fossil energy supplies. The non-agricultural energy demand is given by an upward sloping demand curve, the aggregate energy demand is a sum of agricultural and non-agricultural energy demand.

The representative agricultural farm maximises profits $\Pi = \sum_i p_i a_i^S(l_i^D, e_i^D) - p_l l_i^D - p_e e_i^D$, which implies the following equilibrium conditions:[7]

$$p_i \frac{\partial a_i^S}{\partial l_i} = p_l \quad \text{for } i = m, f \tag{5}$$

$$p_i \frac{\partial a_i^S}{\partial e_i} = p_e \quad \text{for } i = m, f \tag{6}$$

where p_i is farm output price of commodity $i = m, f$, and a_i^S is the quantity of agricultural output, which is produced using land, l_i^D, and energy, e_i^D, as inputs by taking the land rental price, p_l, and energy price, p_e, as given. Equations (5) and (6) are marginal conditions for land and energy inputs, respectively. They determine the equilibrium input demand and output supply.

In Figure 4 the supply of bio**m**ass, a_m^S, and **f**ood, a_f^S, are shown as upward sloping curves (panels a and d, respectively).[8] The aggregate world demand for biomass and food commodity are denoted by $a_m^D(p_m)$ and $a_f^D(p_f)$, and are shown in panels a and d, respectively. The world supply of land is given by $l^S(p_l)$ (not shown).

We assume constant Leontief production technology in bioenergy sector with constant extraction coefficient β. Each unit of biomass results in β units of bioenergy and γ units of waste-product.[9] To simplify the analyses, we assume a constant value of unit processing costs (adjusted for mark-up), c, incurred to bioenergy production from one unit of biomass. This implies that bioenergy supply, $e_b^S(p_e)$, and waste-product supply, $w^S(p_w)$, represent the excess supply of biomass, $a_m^S - a_m^D$, adjusted

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[6] Note that we consider the case where the agricultural commodity suitable for biofuel production may be used both for food and for biofuel production. We denote it as 'biomass' to simplify the exposition.

[7] Superscripts D denote demand, S denote supply.

[8] In Figure 4 we show biomass market (panel a), fuel market (panel b) and food commodity market (panel d) (by-product and land markets are not shown). The effects sown in Figure 4 take into account adjustments in all markets.

[9] We assume that this coefficient also adjusts for quality differences between biofuel and fossil fuel. Hence it represents biofuel in equivalent of fossil fuel.

for the constant extraction coefficients: $e_b^S = \beta\left(a_m^S - a_m^D\right)$ and $w^S = \gamma\left(a_m^S - a_m^D\right)$, respectively, where p_w is the price for waste-product. In Figure 4 bioenergy supply, e_b^S, is shown in panel b.

The world supply of fossil energy together with bioenergy supply generate the aggregate energy supply curve, $e^S(p_e) = e_n^S + e_b^S$, where $e_n^S(p_e)$ is the world supply of non-renewable energy (i.e. other than bioenergy) (panel b in Figure 4). The aggregate energy demand, $e^D(p_e)$, is a sum of agricultural energy demand, $e_m^D + e_f^D$, and non-agricultural energy demand, $e_n^D(p_e)$ (panel b in Figure 4). In order to simplify the analysis, we assume perfect substitutability between bioenergy and fossil energy in consumption.[10]

The equilibrium conditions for agricultural input and output markets can be summarised in five equilibrium conditions. The equilibrium condition for biomass without bioenergy production is given by:

$$\text{if} \quad p_m^0 \geq \beta p_e + \gamma p_w^0 - c \quad \Rightarrow \quad e_b^S = w^S = 0 \quad \Rightarrow \quad a_m^S = a_m^D \tag{7a}$$

where p_m^0 is the equilibrium price for biomass in absence of bioenergy production, p_w^0 is the waste-product price in absence of production of waste-product from biomass. According to inequality (7a), the unit return from biomass, if used to produce bioenergy, is given by the adjusted energy and waste-product prices net of processing costs c: $\beta p_e + \gamma p_w - c$. If the return from bioenergy is smaller than the biomass equilibrium price in the absence of bioenergy production, p_m^0, then bioenergy production is not profitable in equilibrium. In this case the equilibrium biomass price is determined by intersection of biomass demand and supply, $a_m^S = a_m^D$.

The equilibrium condition for biomass in presence of bioenergy production is given by:

$$\begin{array}{ll} \text{if} & p_m < \beta p_e + \gamma p_w - c \quad \Rightarrow \quad e_b^S > 0, w^S > 0 \quad \Rightarrow \quad a_m^S - a_m^D > 0 \\ \text{and} & p_m = \beta p_e + \gamma p_w - c \end{array} \tag{7b}$$

According to inequality (7b), the production of bioenergy is positive, $e_b^S > 0$, if the unit return from biomass used for production of bioenergy is higher than the biomass price, p_m^0, on the food market: $\beta p_e + \gamma p_w - c > p_m^0$. In this case, the equilibrium biomass price is determined by the price for energy and waste-product: $p_m = \beta p_e + \gamma p_w - c$. The food commodity equilibrium is given by:

$$a_f^S = a_f^D \tag{8}$$

The land market equilibrium is given by:

$$l_m^D + l_f^D = l^S \tag{9}$$

The waste-product market equilibrium is given by:

$$w^S = w^D \tag{10}$$

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[10] In reality, fuel containing low share of biofuels (e.g. 10% or less in the case of ethanol) can be used in virtually all standard vehicles. However, fuel with high share of biofuels requires engine adaptation, which implies additional (fixed) costs to consumers. Hence, depending on the relative importance of these adjustment costs, the theoretical model may overstate the impact of biofuels on agricultural prices.

where $w^D(p_w)$ is the waste-product demand. The energy market equilibrium is given by:

$$e^S = e^D \tag{11}$$

Equation (11) is the clearing condition for the aggregate energy market, where $e^S = e_n^S + e_b^S$ and $e^D = e_n^D + e_m^D + e_f^D$.

Figure 4 shows the equilibrium prices and quantities for biomass market (panel a), energy market (panel b) and food market (panel d). The equilibrium price and quantity for biomass is p_m^0, a_m^*, the equilibrium price and quantity for energy is p_e, e^*. There is no bioenergy production in equilibrium, because the return from biomass for bioenergy production would be lower than the price obtained if sold as food. With energy price p_e, the unit return of biomass for bioenergy production is given by p_m $(= \beta p_e + \gamma p_w^0 - c)$. As shown in panel a, food price is lower than the equilibrium price for biomass, $p_m < p_m^0$, implying no bioenergy production in equilibrium.[11] Finally, the equilibrium price and supply of food is p_f, a_f^*.[12]

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[11] Note that the fuel price is equivalent to return from the biofuel production at price of biomass. Everything else equal, the biofuel production is profitable for fuel prices higher than p_e.

[12] As noted above, we assume that this commodity is used only for food production.

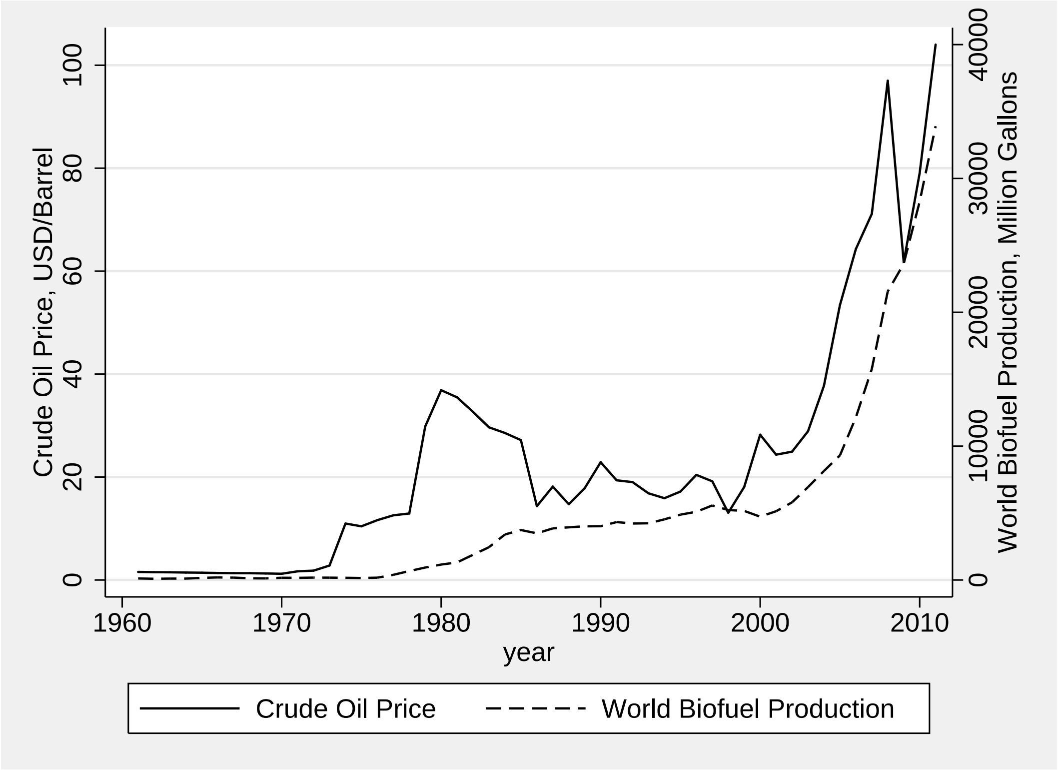


Figure 1: Crude Oil Price, USD/Barrel and World Biofuel Production, Million Gallons 1961-2011. Source: Authors estimations based on World Bank, IAA and Earth Policy Institute data.

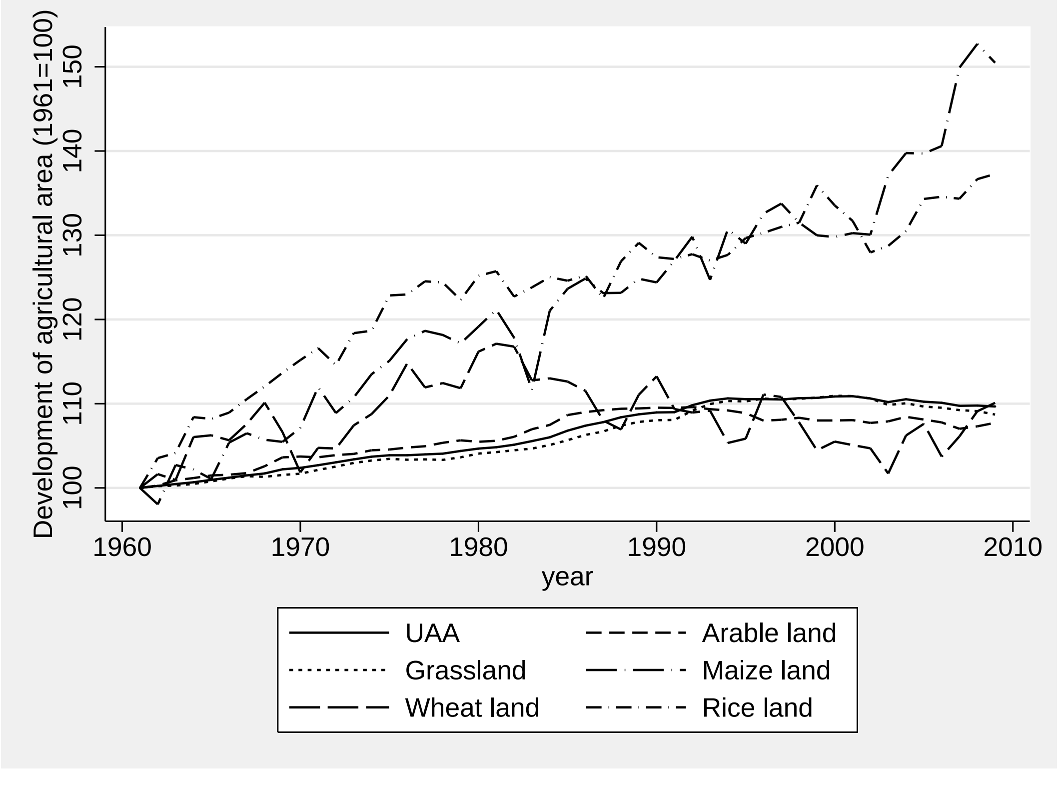


Figure 2: Development of global agricultural area by commodity type, 1961=100. Notes: UAA - Utilised Agricultural Area. Source: Authors estimations based on FAO data.

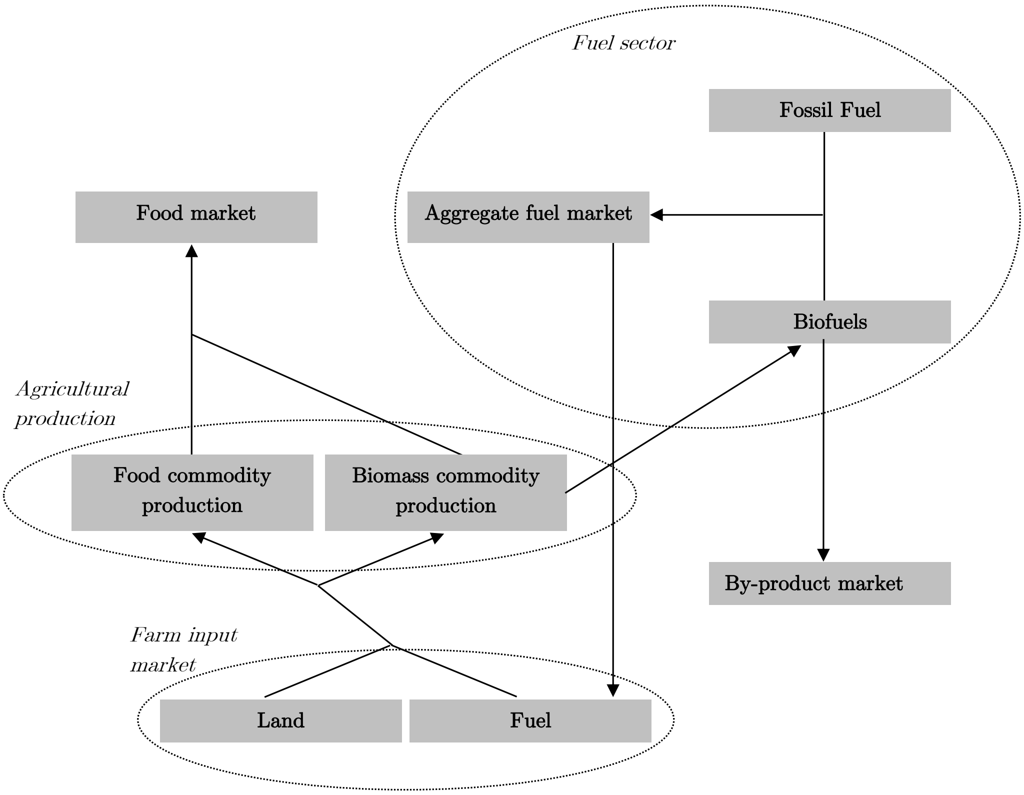
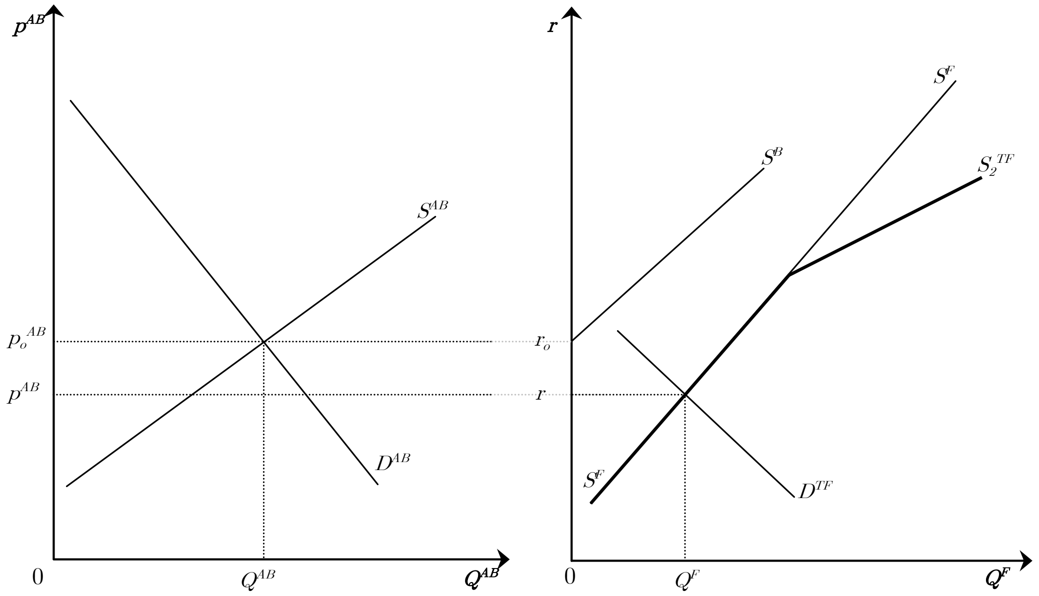


Figure 3: Structure of the model



(a) Biomass Market

(b) Fuel Market

(d) Food commodity market

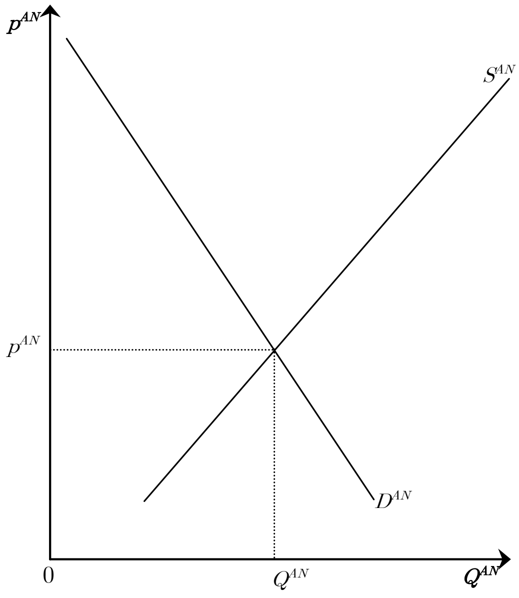


Figure 4: Structure of the model: biomass, fuel and food commodity markets

Table 2: 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: *** denotes significance at 0.01 level, ** at 0.05 level and * at 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 3: 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 2, 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 4: 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: *** denotes significance at 0.01 level, ** at 0.05 level and * at 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 5: 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: 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 4, 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.