AN ASSESSMENT OF THE GLOBAL LAND USE CHANGE AND FOOD SECURITY EFFECTS OF THE USE OF AGRICULTURAL RESIDUES FOR BIOENERGY PRODUCTION

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Abstract

The use of residues and waste is frequently suggested as a way to avoid undesirable land use change and food security effects arising from the use of crops for energy production. We conclude that the that use of the global sustainable potential of agricultural residues for bioenergy in 2030 contributes to an improvement (on average) of food security. The net land use change effects are limited as a result of the expansion of cropland at the expense of pastures. These results are based on the principle that the use of, for example, wheat straw increases the profitability of wheat production, which creates an incentive to produce more wheat. This concept is implemented in MAGNET, a computable general equilibrium (CGE) model, based on the sustainable potential of agricultural harvest residues in the world in 2030 as a case study. Results show that the use of agricultural residues decreases the price of crops, and increases the production and consumption of crops in the regions with high sustainable potentials of agricultural residues (North America, Asia Stan countries, South East Asia and Indonesia). The use of land for crops in these four regions also increases, which is almost fully compensated by a lower use of pasture land. Agricultural land use in the rest of the world decreases due to increased exports of crops and other agricultural commodities from these four regions and a reduction in imports to these regions. The shift of agricultural production from the rest of the world to the four key regions results in higher world average yields and lower agricultural land use globally.

Keywords: indirect land use change, residues, waste, food security, bioenergy

1. Introduction

Biomass is projected to become an important source of energy during the coming decades if climate change policies are implemented to keep the mean increase in global temperature below 2°C above pre-industrial levels policy target (IEA, 2013, IPCC, 2014). However, there are major concerns about the sustainability of supply of biomass. Especially the use of land for the production of energy crops is controversial, because of competition with food production and the resulting effect on food security (HLPE, 2013, Searchinger *et al.*, 2015). Also the impact of bioenergy driven changes in land use on biodiversity and greenhouse gas (GHG) emissions from (decreasing) carbon stocks of natural vegetation are important areas of concern (Ahlgren *et al.*, 2014, Laborde *et al.*, 2014).

In response to these concerns several studies have identified options to reduce or avoid land use change effects (Ernst & Young, 2011, Wicke *et al.*, 2011, Di Lucia *et al.*, 2012). A potentially attractive option is the use of agricultural residues (e.g. straw, stover), forestry residues (e.g. branches, stumps), by-products of food processing industry (e.g. oil cakes) and of the wood processing industry (e.g. bark, sawdust). Also biogenic fraction of municipal solid waste and other types of waste stream (e.g. demolition wood) can potentially provide a sustainable alternative to the use of crops and forest biomass. Also the relatively low costs, compared to dedicated energy crops, make residues and waste an attractive feedstock.

A prerequisite for a sustainable use of residues and waste for energy is that it does not compete with existing or future (non-energy) applications, such as the production of fibre board and animal feed. Another aspect is that part of the residues from agriculture and forestry need to be left on the field to maintain long-term soil fertility and to avoid a decrease of the soil organic carbon content and associated GHG emissions.

Several studies have been carried that evaluate the global sustainable potential of residues and waste (Smeets *et al.*, 2007, Chum *et al.*, 2011, Daioglou *et al.*, 2015, Deng *et al.*, 2015). These assessments of the sustainable potential of residues and waste typically first assess potential from the production and processing of crops, and wood, using 'multipliers' and 'recoverability factors' that account for various theoretical, technical and ecological limitations. Next, the use of residues and waste for other purposes is estimated and subtracted to arrive at the sustainable potential. Estimates of the global potential of residues vary as a result of differences in type of residues and waste streams considered and the assumed 'multipliers' and 'recoverability factors' and differences in technical and economic limitations. The IPCC estimates the worldwide potential of forest and agriculture residues in 2050 at 50-140 EJ, whereby the low and upper bandwidth are classified as having a high and low level of agreement in the literature (IPCC, 2014). According to another recent assessment of the global availability of residues and waste for bioenergy the theoretical potential is projected to increase from 116 EJ per year to 140-170 EJ in 2100, most of which comes from agriculture (Daioglou *et al.*, 2014). Approximately 35% of this potential needs to be left on the field to prevent soil erosion and a further 20-35% is needed for alternative uses. More than 85% of the remaining potential (56-61 EJ in 2100) is available at relatively attractive costs levels assuming that ambitious climate change policies are implemented.

A potentially important aspect is that the studies and policies discussed above ignore economic mechanisms that can cause changes in production and consequently land use change and food security effects. First, the collection of residues[1] require labour, capital and other inputs, which increases the price of these inputs in the agricultural sectors and in other sectors of the economy. Second, the nutrients contained in the straw that is removed from the field need to be compensated by an increased use of fertilizers to maintain the long-term soil fertility. Analyses with the GTAP-BIO multiregional computable general equilibrium model show that the use of corn stover for production of biofuel in the US has only a marginal effect on the price of these inputs (2013). As a result the indirect land use change effects are insignificant.

Potentially more important is that the use of agricultural residues provides an incentive to increase the production of the main product, i.e. the crop that produces agricultural residues as by-product (2009). The rationale is that the crop sector receives income from the production and sale of agricultural residues, experiences an incentive to increase the production of the main product, both in absolute terms and relative to other crops (assuming the price of collection of residues is higher than the production costs). Based on the above rationale Winston (2009) formulated a theoretical framework for assessing the land use change and food security effects of the use of residues based on the USAGE dynamic computable general equilibrium model of the US economy. In this framework the rent of the production of residues, defined as the difference between the price and costs of residues, are considered as a subsidy on the purchaser's price of the primary product.

Therefore, the objective of this study is to evaluate the land use change and food security effects of the production and sale of the global sustainable potential of agricultural residues in the year 2030. This study is based on an impact assessment of the use of wheat straw in the EU (Smeets *et al.*, 2015). First, the conceptual framework of Winston (2009) is used as basis for evaluating the effects of residues as further explained in Section 2. Second, this framework is implemented in the Modular Applied GeNeral Equilibrium Tool (MAGNET; (Woltjer *et al.*, 2014)), which is a global computable general equilibrium (CGE) (Section 3). Next, a baseline and a counterfactual scenario are implemented in MAGNET. In the baseline scenario the use of residues is limited to conventional residue uses, such as animal bedding. In counterfactual scenario we assume that the sustainable potential of agricultural residues is used for bioenergy, as further explained in Section 4. The MAGNET analyses show the impact of residues use on prices, production, land use, consumption, and trade and also show the underlying economic

[1] From an economic perspective no distinction can be made between waste and residue, since these are outputs of the same production process and assuming a positive price for all outputs. For practical reasons in this paper we only use the term residues from now on.

mechanisms. Results are presented in Section 5, which is followed by a section discussion and conclusions (Section 6).

2. A conceptual framework for assessing the land use change and food security effects of residues

In this paper a relatively simple conceptual framework is proposed for evaluating the land use change and food security effects of the use of the sustainable potential of agricultural residues for energy. The sustainable potential is defined as the amount of residues that can be harvested taking into account theoretical, technical and ecological limitations, minus the demand for residues for other purposes.

Figure 1 Demand and supply schedule for residues

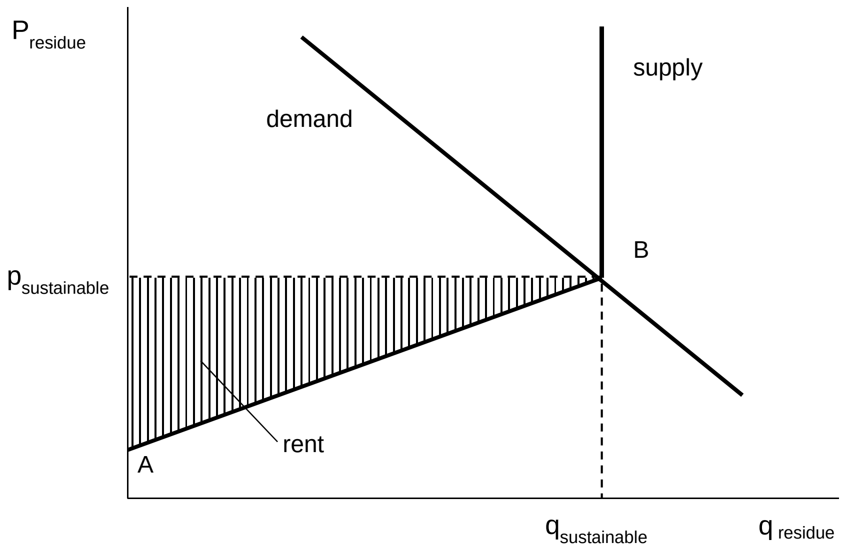


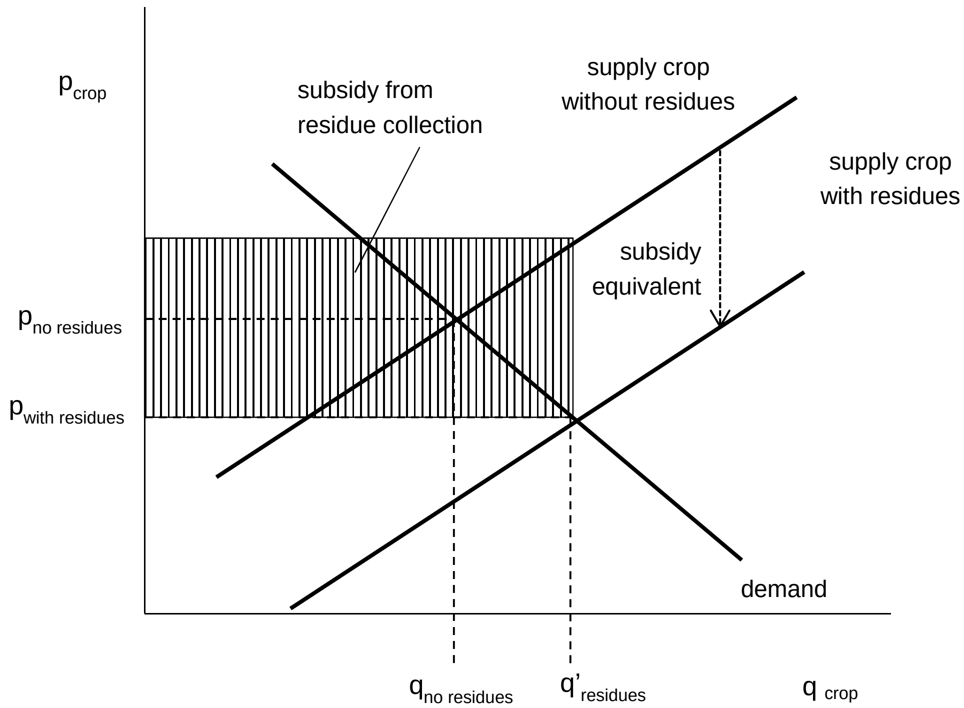
Figure 1 shows the demand and supply of residues under ceteris paribus conditions, i.e. if nothing else changes in the economy. The maximum sustainable residues production, at a given level of crop production, is marked as point B on the residues supply curve and is called $q_{sustainable}$, which is realised when the price of residues is equal to $p_{sustainable}$. On part AB of the supply curve, the demand for residues is less than the available sustainable potential. From point B onwards more residues can only be produced by expanding the production of crop, which is represented by an inelastic supply curve, following Winston (2009).

The rent of the use of the sustainable potential of residues is defined as the difference between the production costs and price of residues (Figure 1). Based on the approach of

Winston (2009) the rents can be considered as subsidy to the production of crops. In other words, profit maximizing producers of crop, with perfect competition, will accept a lower price for every quantity of crop that is covered by the rent of residues. The rents will shift the supply curve of crops downward (Figure 2). This will result in a new equilibrium price of crops when residues are collected - $p_{residues}$ -, which is lower than the price without additional income from residues $p_{no\ residues}$.

At the new equilibrium, the demand for crop and thus total production of crop will be higher. The increase in crop production will be partially realised by an increase in the productivity of land (e.g. by an increased use of fertilizers, labour and capital and other inputs) and partially by increasing the harvested area at the expense of other land using sectors and natural vegetation. We expect that the increase in crop production will result in lower crop prices and higher food consumption and thereby contribute to improved food security. The increase of crop production will also result in an increase of the sustainable supply of residues. Using this additional supply may in turn generate a subsidy effect from the producer's perspective, which will further increase the availability of residues and thus also impacts discussed above.

Figure 2 Crop demand and supply with residues production subsidizing



3. Implementation of the conceptual framework for assessing the land use change and food security effects of residues in MAGNET

The land use change and food security effects of the use of the global sustainable potential of agricultural residues in the year 2030 is analyses using the Modular Applied GeNeral Equilibrium Tool (MAGNET; (Woltjer *et al.*, 2014)). MAGNET is introduced in Section 3.1. Details about the constant elasticity of substitution (CES) nesting structures of crop and animal sectors of MAGNET are discussed in Section 3.2. The production and collection of residues are not explicitly modelled in MAGNET, but is approximated by considering the rents of residues as subsidy to the agricultural sectors as discussed in Section 3.3.

3.1. The MAGNET model

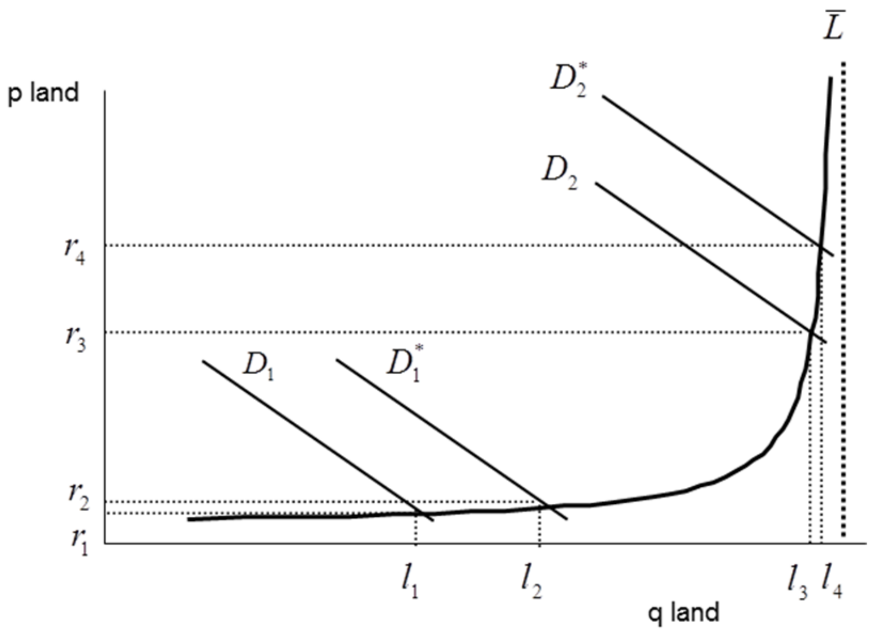
MAGNET (until 2010 referred to as LEITAP) is a global computable general equilibrium model that covers the global economy. MAGNET is based on the Global Trade Analyses Project (GTAP) model that is developed at Purdue University in the United States (Hertel *et al.*, 1997). MAGNET and GTAP are originally designed to model the effects of trade policies, such as the Uruguay Round of multilateral trade negotiations, on especially the agricultural sectors. MAGNET has been extended and updated with several modules to improve the modelling of, among others, land markets and agricultural policies (Van Meijl *et al.*, 2006, Eickhout *et al.*, 2008, Nowicki *et al.*, 2009, Neumann *et al.*, 2011, von Lampe *et al.*, 2014), biofuel policies (Banse *et al.*, 2008, Banse *et al.*, 2011, Prins *et al.*, 2011, Lotze-Campen *et al.*, 2013, Kavallari *et al.*, 2014) and environmental policies and impacts (Stehfest *et al.*, 2006, Tabeau *et al.*, 2011). MAGNET is one of the nine global economic models used for the global model comparison project on the future of agriculture and land use (Nelson *et al.*, 2013, von Lampe *et al.*, 2014).

A more detailed description of relevant modules of MAGNET is given in the sections below. A complete and detailed description of the default version of MAGNET that is used in this study can be found in Woltjer *et al.* (2014). Results are generated based on an aggregated version of the GTAP database version 8 that has 26 regions and 27 sectors. For practical reasons only results for five aggregated regions - North America (Canada and the US), Asia Stan (Kazakhstan, Turkmenistan, Uzbekistan, Afghanistan, Tajikistan, Kyrgyzstan) South East Asia (Laos, Burma, Thailand, Cambodia, Vietnam, Philippines) Indonesia (Indonesia and Papua New Guinea) and Rest of the World – and five crops – rice, wheat, grains, oil seeds and other crops (horticulture, sugar crops and remaining crops) - are shown in this paper.

3.2. Land demand and supply in MAGNET

The supply of land in MAGNET is included using land supply curves (Van Meijl *et al.*, 2006, Eickhout *et al.*, 2009) and depicted in Figure 3. A land supply curve specifies the relationship between land supply and land price, whereby the total availability of land that can be potentially used in agriculture (asymptote; L in Figure 3) is limited by biophysical conditions (climate, soil) and other factors (e.g. distance to infrastructure). As land demand increases, more land is used for agricultural production, which leads to increased land prices.

Figure 3 Land supply in MAGNET



When agricultural land use approaches the total potential land use (asymptote), land is only available at higher prices. As a consequence, in land-abundant regions like South America, an increase in demand from D_1 to D_1^* results in a large increase in land use (from l_1 to l_2) and a modest increase in rental rates (from r_1 to r_2). In land scarce regions, like Europe, a small increase in land demand results in a large increase in the rental rate (shift from D_2 to D_2^* and r_3 to r_4). The assumed land supply elasticities are shown in Annex I.

MAGNET assumes different substitutability between land use types, with the substitution elasticity varying across, but not within, the land use types. This land heterogeneity is introduced in MAGNET using a Constant Elasticity of Transformation (CET) function. In MAGNET the land use allocation structure of the GTAP model is extended by taking into account that the degree of substitutability differs between types of land (Huang *et al.*, 2004). Different types of land use are distinguished with different suitability levels for various crops (i.e. cereal grains, oilseeds, sugar cane/sugar beet and other agricultural uses). The CET elasticities are based on the OECD's Policy Evaluation model (PEM) (OECD, 2003), see also Woltjer *et al.* (2014).

Further, MAGNET has a flexible constant elasticity of substitution (CES) nesting structure for crop sectors. The CES structure for the crop sectors is based on the default version of MAGNET, except that the value added nest is split into a land-fertilizer nest and into a standard value added nest that excludes land. Substitution between land and fertilizer is possible within the fertilizer-land nest. The animal sectors (cattle, milk, pig & poultry in MAGNET) have a similar CES structure as the crop sectors, except that there is no land-fertilizer substitution, but a grassland land - animal feed nest. This nest mimics the substitution between crop and other crops that are used as animal feed (e.g. maize, soybean, crop, beets) and pastures used for grazing. See Woltjer *et al.* (2014) for further information on elasticities and theoretical considerations.

3.3. Implementation of residues in MAGNET

MAGNET does not explicitly distinguish residues as output of the primary agricultural sectors. Therefore, we do not directly include a supply curve for residues in MAGNET as outlined in Section 2 and Figure 2. Instead, we introduce an output subsidy to the primary agricultural sectors equivalent to the rent obtained from the use of sustainable supply of residues c.f. the approach of Winston (2009). The level of subsidies is calculated using exogenous assumptions on the price and production costs of agricultural residues in 2030, as explained in Section 4. We assume that bioenergy production is subsidized by the government, e.g. through a feed-in tariff for bioelectricity, which is a frequently used policy measure to promote renewable electricity production. The impact of the change in output subsidy on government expenditures and taxes on land use change and food consumption are ignored. Reason is that we expect that impacts on land use change and food consumption are very limited, because the effects are diluted across the economy (see further Section 6 Discussion and conclusions).

4. Scenarios

First, MAGNET is used to create a business as usual (BAU) database for the year 2030 (Section 4.1). Second, the global sustainable potential of agricultural residues in 2030 is derived from literature and rents are calculated (Section 4.2). Third, a comparative static counterfactual scenario, called residues bioenergy scenario, is implemented to show the impact of the production and sale of the global sustainable potential of agricultural residues in the year 2030 (Section 4.2).

4.1. Business As Usual (BAU) scenario

The database used in MAGNET is the 2007 GTAP database version 8 (GTAP, 2013). To project the development of agricultural production of the world between 2007 and 2030, GDP and population growth are assumed to follow the Shared Socio Economic Pathways (SSP) 2 projections (Arnell *et al.*, 2011) and increases in crop and livestock productivity are based on projections of the FAO (Bruinsma, 2003). Fossil energy prices are included based on projections of the International Energy Agency (IEA, 2011). No changes in the Common Agricultural Policy (CAP) in Europe or other policies are considered. This scenario is referred to as the business as usual scenario (BAU).

4.2. Residues scenario

In the counterfactual 'residues scenario' we assume that ambitious climate change policies are implemented and that bioenergy plays an important role in the supply of renewable energy. According to the IPCC the global use of biomass for energy production will increase substantially to 2030, up to ca. 18% of the total global primary energy supply, which is equal to ca. 100 EJ biomass (IPCC, 2014).

In this study, we use results from a recent assessment of the sustainable potential and production costs of agricultural residues in 2030 (Daioglou *et al.*, 2015). This assessment is based on analyses with the integrated assessment model IMAGE (Stehfest *et al.*, 2014). Supply curves are available for harvest residues from 10 crop types (temperate cereals, rice, maize, tropical cereals, pulses, roots and tubers, oil crops, vegetables, fruit crops, fibre crops and sugar crops). First the theoretical potential of agricultural residues is calculated using IMAGE projections for 2030 about crop production and crop yields and residue to product ratio and residue to crop area factors. Next, the ecological potential has been estimated by assuming that 200 tonne residue per square km needs to be left on field to protect the soil from wind and water erosion. Alternative uses of agricultural residues, e.g. for animal feed and traditional bioenergy use (e.g. cooking stoves), are deducted from the ecological potential to arrive at the sustainable available potential. Finally, supply curves for the sustainable potential are calculated by spatially explicit analyses that consider location specific collection and transport costs.

The total global sustainable potential of agricultural residues is calculated at 13.5 EJ in the year 2030, which is less than the 100 EJ bioenergy demand projected by the IPCC for 2030 (IPCC, 2014). Based on this and on the relative low costs of residues compared to biomass from plantations and taking into account policies that specifically stimulate the use of residues we assume that the 13.5 EJ sustainable potential of agricultural residues is fully utilised for bioenergy. Further, for each of the 26 MAGNET regions residues supply curves are used from Daioglou et al. (2015) to determine the rent of agricultural residues per region as depicted in Figure 1. The sustainable potential of agricultural residues and the rents of the sustainable potential of agricultural residues are shown in the table below (Table 1). The data in this table are shown for four regions that have the highest sustainable potential of agricultural residues and are reclassified to the crop sectors in MAGNET.

Table 1 The global potential and rent of agricultural residues in 2030. Source: Daioglou et al. (Daioglou *et al.*, 2015)

	Rice	Wheat	Grains	Oil-seeds	Other crops	Total
Potential (EJ)						
North America	0.1	0.5	1.8	0.8	0.0	3.2
Asia Stan countries	0.0	2.4	0.9	0.0	0.3	3.5
South East Asia	1.5	0.0	0.1	1.5	0.0	3.1
Indonesia	0.7	0.0	0.1	1.6	0.0	2.5
Rest of the World	0.1	0.4	0.5	0.2	0.1	1.2
Total	2.4	3.3	3.3	4.1	0.4	13.5
Rent (billion US$)						
North America	0.2	1.0	4.3	1.8	0.0	7.4
Asia Stan countries	0.0	1.1	0.5	0.0	0.1	1.7
South East Asia	0.5	0.0	0.0	0.4	0.0	0.9
Indonesia	0.2	0.0	0.0	0.5	0.0	0.8
Rest of the World	0.0	0.3	0.3	0.1	0.0	0.8
Total	0.9	2.4	5.1	2.9	0.2	11.6

The sustainable potential of agricultural residues is concentrated in four regions: North America, the Asia Stan countries, South East Asia and Indonesia. Each of these regions contribute about one-fourth to one-fifth to the global potential. Half of the global potential of residues comes from wheat and grains; both crops contribute 3.3 EJ. Rice and oilseeds account for 18% and 30% to the global potential, respectively. According to results from Daioglou et al. (2015) the average costs of collection of residues are 2.6 $/GJ, the price (i.e. $p_{sustainable}$ in Figure 2) is 3.4 $/GJ and the average rent is 0.9 $/GJ. The region with the highest average rent is North America (2.3 $/GJ), followed by the Asia Stan region (0.5 $/GJ) and South East Asia and Indonesia (both 0.3 $/GJ). The total global rent is 11.6 billion $. 46% of comes from North America, 14% from the Asia Stan countries, 8% and 7% from South East Asia and Indonesia, respectively. Grains have the highest rent, 5.1 billion $, or 43% of the total global potential. This also means that 38% of the global rent of harvest residues comes from the grains sector in North America.

5. Results

Results are presented below, starting with the effect on prices, followed by the impact on consumption and food security, production, trade and land use.

Prices

The rent of harvest residues increases the profitability of crop sectors that deliver these residues. The additional rent results in lower (market) prices of crops in the regions and sectors that supply these residues when compared to the BAU scenario. The largest price effects are projected to occur in the Asia Stan countries: prices decrease by 4.2% (rice), 9.9% (wheat) and 11.5% (grains). Prices of wheat and grains and oilseeds in North America are 2.3-4.1% lower according our calculations. The price decrease is less in the other two regions with large residues potentials (South East Asia and Indonesia). These differences are caused by, among others, the size of rent effect compared to the total production value. The rent of harvest residues from wheat and grains in the Asia Stan countries is equal to 24% of the production value in the BAU scenario, and 5.1-6.1% for wheat and grains in North America, compared to 3.7% or less in other regions. Consequently, the average price of crops decreases more in the Asia Stan region (3.2%), compared to North America (1.7%), South East Asia (0.7%) and Indonesia (0.9%).

The lower price of crops in the four regions is (partially) transferred across the world through changes in production, consumption and trade of crops, meat and processed foods. Wheat and grains prices in the rest of the world decrease by 1.1% and 1.4%, respectively. The price of oilseeds in the rest of the world decreases (1.1%) and of rice (0.5%). The global average price of crops is 0.5% lower compared to the BAU scenario.

Table 2 Crop prices in the residues scenario compared with the BAU scenario (in % change).

	Rice	Wheat	Grains	Oil-seeds	Other crops	Average all crops
North America	-2.3	-2.4	-4.1	-2.8	0.2	-1.7
Asia Stan countries	-4.2	-9.9	-11.5	1.1	0.8	-3.2
South East Asia	-1.4	-1.2	-0.2	-1.4	0.0	-0.7
Indonesia	-1.4	-1.1	0.3	-2.3	-0.1	-0.9
Rest of the World	-0.2	-0.7	-0.5	-0.6	-0.1	-0.2
World	-0.5	-1.1	-1.4	-1.1	-0.1	-0.5

Lower crop prices result in an increased consumption and production of crops and other agricultural commodities (as further discussed in the paragraphs below). The expansion of production is partially realised by higher yields per hectare and partially by increases in agricultural land use (see further the section on land use). Consequently the price of agricultural land in the four regions also increases. The average price of agricultural land in North America and in the Asia Stan countries increases 5.6% in both regions, compared to 0.7% and 0.6% in South East Asia and Indonesia, respectively. In the rest of the world the price of agricultural land decreases 0.4%. The higher price of agricultural land, in combination with the limited rent of agricultural residues (Table 1), also explains the increase in production costs and prices of other crops in North America, the Asia Stan countries and South East Asia.

The higher price of agricultural land in the four regions increases the production costs in all agricultural sectors, including the animal production sectors that use pastures (i.e. the milk and the cattle sector). This effect counteracts the impact of lower prices of crops on the production costs of the milk and cattle sectors, as these sectors both use land (i.e. pastures) and crops (mainly wheat, grains and oilseeds). The net effect on the prices of meat and dairy prices depends, among others, on the relative changes in prices. Producer prices of cattle meat, other meat and dairy products decrease in North America (0.5% maximum), while prices in the other three regions increase (0.9% maximum). Reason is that the cattle and milk sector in North America use more crops compared to the other three regions. Prices of meat and dairy decrease in the rest of the world, due to lower prices of both agricultural land and crops. The global average prices of cattle meat decreases by 0.2% and of other meat and dairy products 0.1%.

Consumption and food security

The lower prices of crops increase the consumption of crops and processed foods, both in the four key regions and in other parts of the world, although there are a few exceptions (Table 3). The consumption of rice, wheat, grains and other crops increases, except of grains in Indonesia and oil seeds and other crops in the Asia Stan countries. The lower consumption of oilseeds and other crops in the Asia Stan region is the result of the higher price of agricultural land (Table 2), in combination with the absence of a production increasing and price decreasing effect of residues from production of these crops (Table 1). The grains sector in Indonesia is relatively small compared to the oilseeds and rice sector. The use of residues from the rice and oilseed sectors increases the price of agricultural land and of grains (Table 2), which also explains the lower consumption of grains in Indonesia.

Table 3 Consumption of crops in the residues scenario compared with the BAU scenario (in % change).

	Rice	Wheat	Grains	Oil-seeds	Other crops	All crops
North America	0.2	0.6	2.6	1.5	0.0	0.9
Asia Stan countries	0.3	5.0	1.9	-3.9	-0.1	1.2
South East Asia	0.3	0.5	0.2	1.2	0.1	0.4
Indonesia	0.1	0.2	-0.2	1.9	0.1	0.4
Rest of the World	0.0	0.1	0.2	-0.1	0.0	0.0
World	0.1	0.1	0.6	0.2	0.0	0.1

The use of wheat and grains in the rest of the world increases, but the use of oilseeds decreases, because of the substitution of oilseeds with wheat and grains and increased use of pastures (as further explained in the paragraph on land use). The global consumption of rice, wheat, grains and oilseeds also increases, compared to the BAU scenario. The strongest increase occurs in the grains sector (+0.6%), followed by the oilseeds sector (+0.2%). These are also the sectors with the highest rents from residues both when expressed in billion US $ and relative to the value of production. On average the use of crops increases 0.1%. 73% of the consumption growth in the world occurs in

North America and 82% of this increase consists of grains. Especially the use of grains by the animal sectors increases. This is caused by scarcity of agricultural land in North America in combination with low household demand for agri-food products resulting from low price elasticities of demand characteristic for high income countries. 64% of the additional grains consumed in North America are used by the cattle, milk and pig & poultry sectors, which is about 40% of the total global increase of consumption of crops. In other words, about 40% of the additional use of crops in the world is used by the animal sectors.

Production

The use of residues in the four key regions increases the production of most crops (Table 4). This goes especially for crops that have substantial sustainable potential of harvest residues, such as wheat and grains in North America and the Asia Stan countries and the oil crops sector in North America. Wheat and grains production in the Asia Stan countries increases 14.3% and 4.0%, respectively. The output of the oilseeds sector in the Asia Stan area decreases (5.8%), due to higher prices of agricultural land and production costs and prices (Table 2) and the substitution of oilseeds by grains and wheat for use as animal feed. The lower production of wheat and grains in South East Asia and Indonesia is caused by a reduced competitiveness compared to the oilseeds sector due to the higher rent of oilseed residues. Note that the relative changes shown in Table 3 provide no insight in the absolute changes in production. 74% of the increase in production occurs in North America, followed by the Asia Stan area; South East Asia and Indonesia each contribute 6%.

Table 4 Production of crops in the residues scenario compared with the BAU scenario (in % change).

	Rice	Wheat	Grains	Oil-seeds	Other crops	All crops
North America	2.9	4.7	3.0	3.0	-0.3	1.6
Asia Stan countries	0.7	14.3	4.0	-5.8	-0.1	3.7
South East Asia	0.3	-2.5	-0.2	1.3	0.0	0.4
Indonesia	0.1	-2.0	-0.2	2.0	0.1	0.4
Rest of the World	0.0	-0.7	-0.2	-0.7	0.0	-0.1
World	0.1	0.1	0.6	0.2	0.0	0.1

Important to note is that the production of wheat, grains and oilseeds in the rest of the world decreases, 0.7%, 0.2% and 0.7%, respectively. The reason is that the rent from agricultural harvest residues increases the competitiveness of the agricultural sectors in the four regions with large potentials and rent effects (Table 1), compared to other crops and regions. The net effect is a shift in production from the rest of the world to the four regions. Globally, about 60% of the increase in crop production in North America, the Asia Stan countries, South East Asia and Indonesia is undone by the decrease in crop production in the rest of the world.

Interesting is that the consumption of crops in the rest of the world does not change, despite the decrease in production due to increased imports (as further explained in the section on trade). Also the production of livestock, meat, milk and of the crop and food processing sectors (sugar, vegetable oils, and processed food products) increases in the rest of the world, despite the decrease in production of crops in this region. These effects are the combined result of lower prices and increased imports, as further explained in the next paragraph.

Trade

This paragraph shows that the impact trade of agricultural commodities is crucial when interpreting the production and consumption effects. Table 5 shows the percentage change in export and import of agricultural commodities.

The changes in prices (Table 2) consumption (Table 3), production (Table 4) are reflected in the change in trade patterns. The largest trade effects occur in the sectors and regions that experience the largest rent effect and production growth (i.e. especially the wheat and grains sector in North America and the Asia Stan countries and also oilseeds in North America and Indonesia; Table 1). Exports and imports of these crops increases and decrease, respectively, in these regions. The export of wheat and grains from the Indonesia region and South East Asia declines and imports increase, due to higher production costs (higher land prices) from the growth in oilseed production.

The aggregated effects are increased exports from, and decreased imports to, the four regions with large rents from agricultural residues. Most important is the export growth from North America, which accounts for 82% of the aggregated increase of exports in the four regions. Note that the change in imports is only 5% of the change in exports. The opposite trade effect occurs in the rest of the world. Interesting is the share of the additional production in the four key regions that is exported. On average 48% of the additional production of crops in the four regions is exported. This figure is 60% when also the trade of vegetable oils is considered as most of the oilseeds produced in South East Asia and Indonesia are processed domestically to vegetable oils. In the four sectors and regions with the largest rents of agricultural residues (wheat, grains, oilseeds in North America and wheat in the Asia Stan region; Table 1) circa 60% of the additional crop production is exported. The increased imports of agricultural commodities to the rest of the world more than compensate the decrease of production of crops in these regions. The increase in supply of crops in the rest of the world is used, among others, for the production and consumption of animal products and processed foodstuff in this region.

Table 5 Export and import in the residues scenario compared with the BAU scenario (in % change).

Export	Rice	Wheat	Grains	Oil-seeds	Other crops	All crops
North America	8	6	4	5	-1	3
Asia Stan countries	38	100	30	-9	1	21
South East Asia	4	-1	-2	0	0	0
Indonesia	4	-5	-3	5	0	0
Rest of the World	-8	-7	-1	-3	0	0
World	0	0	0	0	0	0
Import	Rice	Wheat	Grains	Oil-seeds	Other crops	All crops
North America	-9	-8	-3	-5	0	0
Asia Stan countries	-16	-51	-15	-2	1	-2
South East Asia	-7	1	1	1	0	0
Indonesia	0	0	2	1	0	0
Rest of the World	8	10	4	5	-1	3
World	0	0	0	0	0	0

Land use

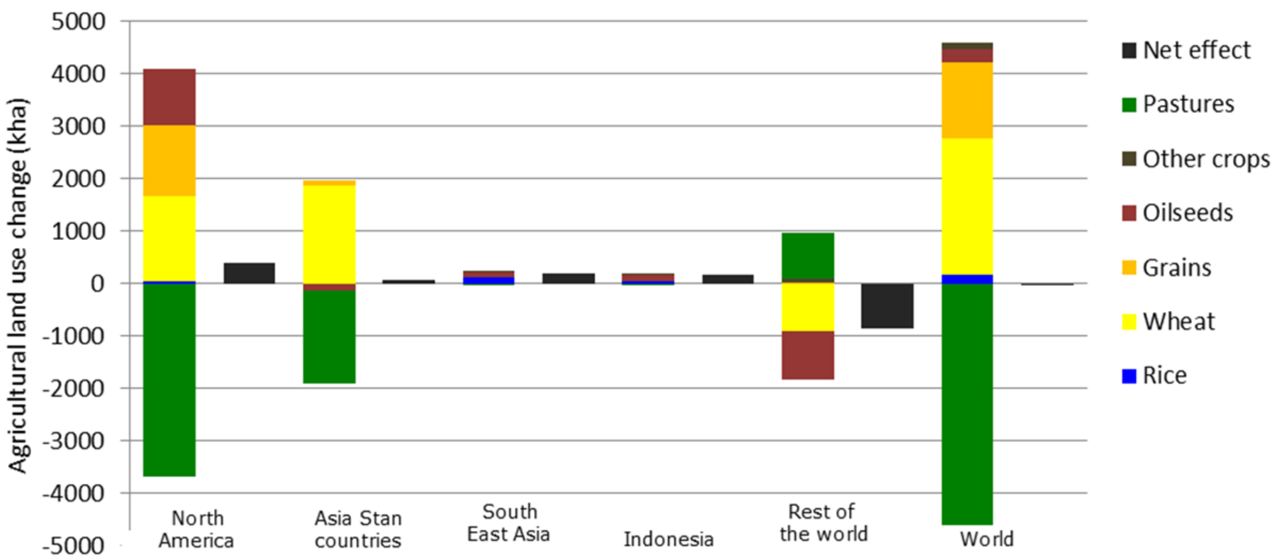
The use of the sustainable potential of agricultural residues for energy leads to a shift in production of crops from the rest of the world to the four regions that have a high potential of agricultural residues (Table 4). The increase in crop production in North

America, the Asia Stan countries, South East Asia and Indonesia is partially realised by expanding the use of agricultural land and partially by higher yields.

The largest increase in crop production area occurs in the regions and sectors with the highest potential and rent of agricultural residues. The area wheat in North America increases 1631 kha and in the Asia Stan countries 1874 kha. Grains and oilseeds acreage in North America goes up by 1361 ha and 1056 kha, respectively. These four combinations of crops and regions are responsible for more than 90% of the total increase in cropland in the four regions (6288 kha). The increase in cropland in these regions is counteracted by a decrease in pasture areas (5484 kha). This effect is mainly the result of the increased use of crop as animal feed, which substitutes the use of other feed and pastures. The area pastures in North America decreases 3667 kha and in the Asia Stan countries 1790 kha. In other words, more than 90% of the cropland expansion occurs on pastures and the net increase in cropland is limited.

Also relevant is the expansion of rice and oilseeds area in South East Asia and oilseeds in Indonesia. The area pastures in these regions is relatively limited compared to the area cropland. Therefore, the expansion of rice and oilseeds production in these regions results in a relatively high expansion of agricultural land when compared to North America and the Asia Stan countries. Agricultural land use in the rest of the world decreases, as a result of the shift in production from the rest of the world to the four regions. The area pastures in the rest of the world increases (867 kha), which limits the decrease of the agricultural area (856 kha) to about half of the decrease of cropland (1722 kha).

Figure 4. Agricultural land use compared with BAU scenario (in kha).



Crucial for the land use change effects projected by MAGNET are the supply and demand of land, as explained in Section 3.2. The production of wheat, grains and oilseeds in North America increases 4.7%, 3.0% and 3.0% (Table 4), respectively, which is more than the growth in cropland of 3.5%, 1.8% and 1.8%. Also wheat production in the Asia Stan area increases more than the area cropland. These results show that the growth of cropland accounts for 60-86% of the production expansion effect in these sectors and regions. The remaining 14-40% comes from higher yields per hectare. These results can be explained by the land supply function in MAGNET (Figure 3), which shows that an increase in the demand for land results in increased scarcity of land and therefore higher land prices and higher yields. The price of land in North America and the Asia Stan countries increases by on average 5.6% in both regions. The higher price of land results in the substitution of land with other production factors (fertilizers, capital, and labour). The area pastures in both regions is relatively large, compared to South East Asia and Indonesia, which also means that the contribution of yield increases to production growth is higher in South East Asia and Indonesia (90% of the additional demand is realised through higher yields) compared to North America and the Asia Stan countries.

The opposite effect occurs in the rest of the world. The decrease in production partially comes from lower use of cropland and partially from lower yields. The net effect is that the average global productivity of wheat decreases slightly (0.4%), as a result of the shift of wheat production to the Asia Stan region, which has a relatively low yield. The productivity of grains and oilseeds increases (0.5% and 0.6%, respectively). Reasons for this are the high(er) yields of grains in North America and the high(er) yield of palm oil in South East Asia/Indonesia (compared to other oil crops produced in other regions).

Globally the area cropland increases (4588 kha) and the area pastures goes down (4618 kha) and the net expansion of agricultural land is limited to 101 kha. The total net impact of the use of agricultural residues is limited, but the underlying shifts in land use can be substantial. The impacts seem limited when expressed in percentage changes, because the effects are diluted across the world. The impacts are however still significant, which is demonstrated by expressing the results per unit residues or biomass. For example, a 1 US$ residues rent increases the production and consumption of (primary) agricultural commodities by 18 US$cent. Relevant are also the land use change effects per unit biomass and bioenergy, since the use of residues is proposed as a way to avoid undesirable land use change and food security effects of first generation biofuels. If we assume a 50% conversion efficiency in 2030 of biomass to second generation biofuel (Van Vliet *et al.*, 2011) than according to the results in this paper the net land use change effects are virtually zero. The area pastures decreases 0.34 Mha/EJ biofuel and the area cropland increases with the same amount. Important is that the conversion of pastures can results in substantial GHG emissions from the loss of carbon sequestered in grasslands. For comparison, the land use change effects of the first generation biofuel blending mandate in the EU are estimated at 2.7-2.9 Mha/EJ and; crop specific values for ethanol are 0.35-1.67 Mha/EJ and for biodiesel 2.0-3.8 Mha/EJ (Laborde, 2011).

6. Discussion and conclusions

The objective of this paper is to evaluate the land use change and food security effects of the use of agricultural residues for bioenergy production. A conceptual framework for analysing these effect is used that considers the impact of the use of residues on the profitability of the agriculture and forestry sector(s) that receive income from the production and sale of these residues. This conceptual framework is implemented in the MAGNET computable general equilibrium model (CGE) model, based on the use of the sustainable potential of agricultural residues available in the world in 2030. The analyses presented in this paper are a first step towards more complex analyses. Potentially interesting topics for future research are:

- We conclude that the use of agricultural residues will, on average, have a positive impact on food security. However, the food security effects may differ per country and per population group. Urban households and other households not involved in agriculture benefit most from the decrease in food prices; rural households that get income from agriculture benefit less due to the decrease in income. These income effects depend on, among others, the flexibility labour and capital markets (e.g., the assumed (un)employment level, segmentation of markets between sectors), the labour intensity of the collection of agricultural residues and the distribution of costs of bioenergy policies between regions and crops. More detailed general equilibrium analyses are required that take into account the impact on income and prices of different households.
- Another aspect that is ignored in our assessment is the impact of the use of agricultural residues on crop production technology. For example, a high(er) price of wheat straw can induce a shift from modern varieties, which have a relatively high grain to straw ratio (0.5) to traditional varieties that typically have a much lower harvest index (0.3) (Gibson, 2012). The net effect is a decrease in wheat yield. Other advantages of traditional varieties are the lower costs of fertilizers and pesticides, better agro-ecological performance (more extensive rooting system, less climate sensitive, better grain quality) (Desai *et al.*, 1978, Richards *et al.*, 2002, Guarda *et*

al., 2004, Barraclough *et al.*, 2010). Another potentially important effect is that the use of wheat straw has complex effects on soil physical properties, such as water-retention (Blanco-Canqui *et al.*, 2009, Powlson *et al.*, 2011). In areas where wheat yields are limited by water the removal of straw will reduce yields, at least in dry years. The use of agricultural residues can thus lead to changes in the crop yields and cost structure of crop production (different input costs) and another benefit structure (e.g. higher prices for improved grain quality). The impact of these developments on the results is difficult to quantify, because of the partially counteracting effects, such as the decrease in crop yields and production costs.

- Further, it is also important to note that in this study the sustainable potential of agricultural residues in the EU is implemented in MAGNET in stylised manner, using exogenous assumptions about the sustainable potential of agricultural residues. A drawback of this approach is that competing uses of agricultural residues are given priority above the use for bioenergy. In reality the use of agricultural residues for bioenergy in the EU will influence the demand for biomass for other applications and also the supply of biomass from other sources (residues and waste from other agricultural sectors or the forestry sectors) and other regions. These aspects are not considered in this study. These issues may change the use of residues for bioenergy production, depending on the dynamics of supply and demand.
- The focus of this paper is on land use and the impacts on GHG emissions of bioenergy use are not calculated. The assessment of GHG emission effects require additional calculations that, among others, take into account changes in the carbon stored in above- and belowground biomass. Crucial thereby is that the removal of agricultural residues changes the soil organic carbon content. The volume of carbon stored in the soil is so large, that even small changes have a significant effect on the GHG balance of bioenergy systems (Liska *et al.*, 2014). Also important is that the removal of residues influences nitrous oxide (N_2O) emissions, although the direction of the impacts varies according to the conditions (Powlson *et al.*, 2011).

Despite these uncertainties and research challenges we conclude that consideration of the land use change and food security effects is thus crucial for a truly sustainable use of residues and waste for bioenergy and therefore also for the effectiveness and efficiency of bioenergy policies.

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