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A scenario based analysis of land competition between food and bioenergy production in the US

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Abstract Greenhouse gas abatement policies will increase the demand for renewable sources of energy, including bioenergy. In combination with a global growing demand for food, this could lead to a food-fuel competition for bio-productive land. Proponents of bioenergy have suggested that energy crop plantations may be established on less productive land as a way of avoiding this potential food-fuel competition. However, many of these suggestions have been made without any underlying economic analysis. In this paper, we develop a long-term economic optimization model (LUCEA) of the U.S. agricultural and energy system to analyze this possible competition for land and to examine the link between carbon prices, the energy system dynamics and the effect of the land competition on food prices. Our results indicate that bioenergy plantations will be competitive on cropland already at carbon taxes about US \$20/ton C. As the carbon tax increases, food prices more than double compared to the reference scenario in which there is no climate policy. Further, bioenergy plantations appropriate significant areas of both cropland and grazing land. In model runs where we have limited the amount of grazing land that can be used for bioenergy to what many analysts consider the upper limit, most of the bioenergy plantations are established on cropland. Under the assumption that more grazing land can be used, large areas of bioenergy plantations are established on grazing land, despite the fact that yields are assumed to be much lower (less than half) than on crop land. It should be noted that this allocation on grazing land takes place as a result of a competition between food and bioenergy production and not because of lack of it. The estimated increase in food prices is largely unaffected by how much grazing land can be used for bioenergy production.

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1 Introduction

The global demand for bioproductive land is expected to increase. First, one can expect an increased demand for food and for animal products in the diet as a consequence of population and income growth (Yotopoulos (1985); Rosegrant and Cline (2003); Dyson (1996); FAO (2003)). Second, energy analysts (Hoogwijk et al. (2005); Berndes et al. (2003)) claim that the use of biomass for energy purposes could increase substantially, as a result of policies to curb growing emissions of CO_2. Scenarios of the future bioenergy supply have suggested that land resources devoted to energy crops could equal the current land used for crop cultivation, i.e. 1,500 Mha (see Berndes et al. (2003) for a detailed review of studies estimating the global potential for biomass). Third, an increased demand for fiber and natural parks can also be expected. In this paper we focus on the competition for land between food and bioenergy.

In order to reduce carbon dioxide (CO_2) emissions cost-effectively, policy instruments such as a carbon tax or a cap and trade system have been suggested and, in certain regions, implemented. These instruments set a price on CO_2 emissions. In the European Union Allowance Trading System (EU ETS), the permit price is currently (November, 2005) about 90 €/ton C, and Sweden has a tax on CO_2 emission of approximately 400 €/ton C. These kinds of measures make energy sources with low greenhouse gas emissions, such as bioenergy, increasingly profitable. In Sweden, the district heating system is now dominated by bioenergy. When profits from biomass plantations exceed profits from food production, farmers will, if they behave as profit maximizers, respond by shifting toward energy crop cultivation unless agricultural commodity prices increase. In Sweden, for example, farmers burn their own cereals to heat their farms. This competition between biomass and food might result in increased food commodities prices.[1]

A common response to the potential competition between energy crops and food crops is to suggest that degraded, rather than prime, cropland could be targeted for bioenergy production, see for example Hall et al. (1993), and SEI (2005).

Further, Hall et al. (1993), and many of the analysts in SEI (2005), argue that it in many cases, but not all, cultivating perennial energy crops on degraded land in developing countries would improve this land, since this would restore soil organic matter and nutrient content, stabilize erosion and improve moisture conditions.

Where bioenergy ought to be cultivated is of course a different question from where it may in fact come to be cultivated. If the allocation of land is done by commercial farmers and companies, they are expected to choose the most profitable land type. There is no a priori reason to think that it is most profitable to choose degraded and lower-quality land.

Degraded land is often inhabited by rural poor who lack formal land property rights. An expansion of bioenergy plantations could lead to the displacement of these rural poor. This question is of course more central to discussions about the establishment of energy plantations in rural areas in developing countries and it will for that reason not be addressed.

This paper presents a model of the interaction between the energy and food systems and climate policy. Earlier studies along these lines include Azar and Berndes (1999); Azar and

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[1] The discussion on how an increased demand for bioenergy affects the agricultural systems and food prices is not new. It was discussed quite intensively about 25 years ago, especially during the oil crises and the start up of bio-alcohol programs designed to decrease the reliance on oil import (Meekhof et al., 1980; Brown, 1980).

Larson (2000); Gielen et al. (2001); McCarl et al. (2000); McCarl and Schneider (2001); Schneider and McCarl (2003); Sands and Leimbach (2003); de la Torre Ugarte et al. (2000); Ignaciuk et al. (2006) and Azar (2005). McCarl and Schneider (2001) and Schneider and McCarl (2003) focus on the interaction between bioenergy as a greenhouse gas mitigation option and other agricultural-related mitigation options in a static agricultural sector model covering the U.S. agricultural system and do not explicitly cover the energy system. Schneider and McCarl (2003) conclude that at a carbon price above US$ 70/t C, biomass for energy dominates all other agricultural mitigation options. de la Torre Ugarte et al. (2000) study the impact of minor increases in the biofuel price on the U.S. agricultural system in a highly disaggregated model and show that energy crops are introduced at energy prices just slightly higher than the prevailing prices.

Gielen et al. (2001) focus on issues regarding biomass for food, timber, fibre versus bioenergy production, availability of land for bioenergy/reforestation, use of biomass in the energy sector under various carbon price scenarios and do not explicitly discuss food prices and quality of land used for bioenergy. Sands and Leimbach (2003) use a top-down economic approach with a highly-aggregated, globally-regionalized agricultural sector and analyze changes in carbon pools and land used for energy crops under various carbon price scenarios. Ignaciuk et al. (2006) study how a carbon tax or a subsidy on electricity produced from biomass affects the Polish agricultural system in a partial equilibrium model. The approach taken by Azar and Berndes (1999) is more qualitative, showing the possible impact of CO_2 abatement policies on wheat prices. They come to the conclusion that wheat prices could more than double if high carbon taxes are introduced globally. Azar (2005) estimated global food and land prices in a global energy system (linear programming) model with increasing carbon taxes over time.

Azar and Larson (2000) analyze the profitability of prime cropland versus low-productive land (degraded land) for energy crop cultivation and conclude that the higher land prices for prime cropland do not discourage cultivation of energy crops. The higher yields expected on prime land make it more profitable for energy crops than low-quality land.

The current study focuses on the U.S. agriculture and energy system to exemplify this land-use competition. The aim of this study is to analyze:

- The impact of stringent CO_2 abatement policies on food and land prices;
- Where it is most cost-effective to cultivate energy crops: on cropland, or on low quality land, namely, grazing land;

Our contribution to this food-fuel competition discussion lies in the integrated modeling of the energy and agricultural sectors in a dynamic framework, a comprehensive sensitivity analysis and an explicit economic analysis of the use of high-quality versus low-quality land for bioenergy cultivation.

By simultaneously modeling the energy and agricultural sectors one can better reflect the interaction between these. The demand for bioenergy depends on the carbon price and on the fuels used on the margin for electricity, heat and transport, respectively. In our model, it is also possible to estimate how various CO_2 emission targets affect food, land and bioenergy prices. Most of the previous attempts, e.g. McCarl and Schneider (2001) and Sands and Leimbach (2003), have assumed a constant fuel on the margin, e.g. coal for electricity production, which is questionable when carbon prices are high. Others, e.g. de la Torre Ugarte et al. (2000), have assumed a constant price for bioenergy.

The paper is organized as follows: in the next section the model methodology and data assumptions are presented. In Section 3 we present scenario assumption. In Section 4 the main results are presented and in the subsequent section we investigate the model sensitivity to critical assumptions. Finally, we summarize our results and conclude.

2 Model methodology

In order to analyze energy, biomass and food interactions, we have developed a dynamic non-linear programming model with decadal time steps, LUCEA 2.0 (Land Use Change Energy and Agriculture Model). The model assumes a competitive market with complete temporal information, i.e. all future costs and benefits are known and taken into account in current decisions; producers behave as price taking profit maximizers, and consumers behave as utility maximizers. These assumptions are implemented by maximizing the net present social payoff (the sum of consumer and producer surplus), resulting in a demand and supply equilibrium (McCarl and Spreen, 1980). CO_2 is the only greenhouse gas considered, and we have not included any biospheric carbon sink options.

The model consists of two modules: an energy system module and an agricultural module, see Fig. 1. In the following two sub-sections, a non-technical presentation of the model is given. For a more technical description of the model, see Appendix A.

2.1 Energy model

The basic structure of the energy supply, conversion, and demand model, and data regarding efficiencies, costs, life times etc. are taken from Azar et al. (2003) and Azar et al. (2006). The primary energy sources considered are natural gas, oil, coal, uranium, wind, hydro, bioenergy and solar energy. These sources can be converted to electricity,

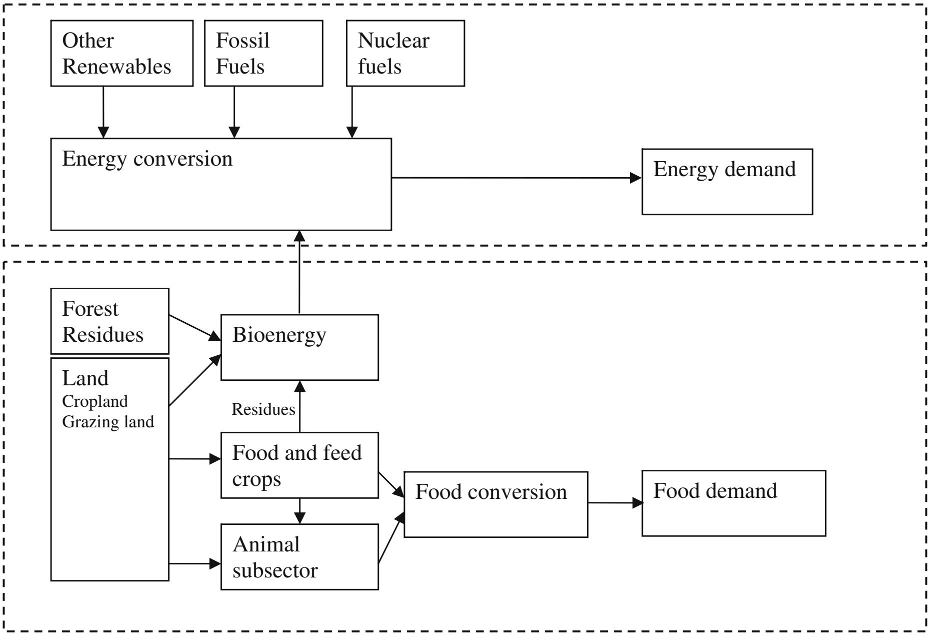

Fig. 1 Graphic representation of the model

transportation fuels or heat which in turn are supplied to the end users. The conversion of primary fuels to end-use energy is modeled through leontief production functions. That is, a fixed amount of primary fuel and fixed amount of energy conversion capital is needed for each unit of end-use energy. Production technologies have an operating life-time of 25 years, except for hydropower stations which have an operating lifetime of 40 years. Differences in end-use technologies are considered for the transport sector. Variations in drive train efficiencies and costs for internal combustion vehicles and hydrogen fuel cell vehicles are taken into account. Costs for transportation fuel distribution are also considered (see Azar et al. (2003), for details).

In the sensitivity analysis we include the possibility of carbon capture and storage (CCS) from combustion of fossil fuel and from the production of electricity, hydrogen or heat from biomass. We assume that 40% of the heat and 80 % of the electricity production can be equipped with carbon capture and storage technologies. We assume a cost of US$ 20/t CO_2 for transport and storage for all captured CO_2. Costs and energy conversion efficiencies for plants with carbon capture are taken from Azar et al. (2006). We assume an upper storage capacity of 200 Gt C, somewhat lower than the capacity for geological storage in Herzog et al. (1997).

The model has price-inelastic demand functions. The elasticity is set to −0.4 for all energy end-use sectors. This is in line with values used by several other modelers, e.g. Loulou and Lavigne (1996) and Manne and Richels (1992). The model is calibrated to match data for 1990.[2]

2.2 The agricultural model

The agriculture model consists of several parts: a resource module (land), a primary production module (vegetative biomass), a secondary production module (meat and vegetable products), and a demand module. Food and feed crops are produced on cropland, grass is produced on grazing land. Conversion efficiency between feed intake and edible animal products is accounted for. Bioenergy can be cultivated on both cropland and to a limited extent on grazing land. Suitable residue flows from the food and forestry sectors are assumed to be eligible for bioenergy.

Land resources are divided into two land classes: cropland and grazing land.[3] Ten regions are considered,[4] giving a total of 20 different land categories. The total land area in each class and region is modeled through the use of supply functions. That is, the land area increases when the willingness to pay for land increases and decreases when the willingness to pay for land decreases. The land supply elasticity is assumed to be 0.1. This corresponds to the land supply elasticity used in the OECD PEM model, OECD (2001). Econometric studies of single crops suggest a higher elasticity, OECD (2001). On the other hand, in our model, the main extra source of new land is forest land, essentially. If clearing of standing forest were priced according to its carbon value, this would likely yield a lower land supply elasticity. In Section 5.3 we assess the sensitivity of the results to changes in this parameter.

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[2] An exact match is hard to obtain due to, among other things, differences in aggregation of end use sectors and fuel categories in the model, as compared to official statistics.

[3] Grazing land is the sum of the classes cropland pasture, grassland pasture and range given in (Vesterby and Krupa 2001).

[4] The regions are the standard USDA production regions: Appalachian, Corn belt, Delta states, Northeast, Lake states, Mountain, Pacific, Southern plains, Northern plains, Southeast.

Table 1 Feed mixes for different production systems assumed in the model, estimated from Church (1991), Wirsenius (2000), and ECN (2004). The values show shares of metabolized energy

	Oil cake	Grazed grass	Corn	Wheat	Hay
Cattle-range	0	0.7	0.3	0	0
Cattle-intensive	0	0.35	0.3	0	0.35
Cattle-industrial	0.1	0	0.5	0	0.4
Milk-range	0	0.4	0.3	0	0.3
Milk-intensive	0	0.3	0.3	0	0.4
Milk-industrial	0.1	0	0.5	0	0.4
Other animal prod.	0.3	0	0.45	0.25	0

A variety of crops (maize, wheat, oil crops, hay, energy crops) can be cultivated on cropland while grass, and to a limited extent, energy crops can be produced on grazing land. The area dedicated to each crop on each land class is decided endogenously in the model, so as to maximize the net social payoff (see Appendix B for calibration assumptions). The total production of each crop (and crop residues) is a function of the land area and other production inputs. The yield is determined by regional differences and a variable that captures all production inputs except land, hereafter called "other inputs." In order to model the combination of inputs and corresponding output, we use a Constant Elasticity of Substitution (CES) production function with an elasticity of substitution (ESUB) of 0.3 between the two inputs,[5] based on data in OECD (2001). The supply of "other inputs" is assumed to be perfectly elastic. This formulation give that yields can increase endogenously in the model when land gets scarce. Such increases could (in the real world) arise if higher land values and crop prices lead to additional or more efficient use of inputs, such as fertilizers and irrigation. Additionally, we assume that crop yields grow exogenously so as to simulate technical progress, e.g. progress in plant breeding. The progress rate drops over time, so that the exogenous yield increase stabilizes at a level of about 30% higher than the yield in 1990, by 2050, see Zuidema et al. (1994). We assume the amount of residue generated from crop production is a fixed fraction of the amount of crop produced. The residue/crop ratios are from Wirsenius (2000).

Animal product production is modeled through the use of leontief production functions. That is, a fixed amount of feed and capital input is needed for each unit of animal product produced. The amount of feed and capital needed is assumed to depend on the animal product and the feed-to-edible-product conversion efficiency. Three different leontief production functions are assumed for cattle meat (which represents all ruminant meat products) and milk production. These production functions are estimated from material in Church (1991), Wirsenius (2000), and ECN (2004), see Tables 1 and 2. Which of the production systems is used is decided endogenously. For other meat products (pork, broiler and egg production), only one leontief function is used. The productivity in animal product production is assumed to increase, with a decreasing growth rate over time, by 15% in the year 2050, see for example Zuidema et al. (1994) and Wirsenius et al. (2004). After 2050, it is assumed to remain constant.

Production of consumer products is also modeled through the use of leontief production functions. That is, a fixed amount of primary vegetable or animal products and capital is

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[5] For some of the crops we have assumed an ESUB of 0.2 so as to avoid unreasonably high yields.

Table 2 Conversion efficiency (energy in edible product/energy in feed) in production of animal products, estimated from Wirsenius (2000)

	Milk (%)	Cattle meat (%)	Other meat (%)
Maize	15.7	3	16
Wheat	15.7	3	16
Oil crops	15.7	3	16
Hay	10.2	2	–
Energy crops	–	–	–
Grazing	10.2	2	–

needed for each unit of the consumer product. The calibration of the leontief function reflects conversion and storage losses, estimated from Wirsenius (2000) and conversion, storage and retail cost margins estimated from ERS (2002b). The demand price elasticity is assumed to be −0.2 (on the price of the final product), a value in between estimates in Huang and Lin (2000) and Regmi (2001).[6]

In the model, bioenergy is produced from either energy crops cultivated on agriculture land, residue flows from the traditional agriculture sector, or residues from the forestry sector. The cultivation of energy crops and the use of crop residues is part of the agriculture model. Energy crops are modeled with CES functions. Unlike other crops, energy crops can be cultivated on grazing land, but with a lower yield (about 70% of the yield achieved on cropland in the same region). The amount of grazing land that can be used for energy crop cultivation is exogenously constrained to 48 Mha, following de la Torre Ugarte et al. (2000) and Graham (1994). We assume that a fixed factor of the total amount of crop residue generated can be used for energy. We have used a recoverability factor for the residues of 25%, and for the forest residues we have used a stepwise supply curve, see Walsh et al. (2000), for both. A total of 3.5 EJ/yr can be supplied from the forestry and paper mill sector, at a cost of US$ 2.5/GJ. We assume that this supply curve is applicable for the entire time period modeled.

2.3 Model limitations

Here we present some model limitations and factors that were not considered in the model and discuss how they may affect the results. These aspects have been neglected since it would have increased the complexity of the model, made it harder to interpret results and increased the computation time, without adding much insight about the key questions we want to study.

Our modelling approach captures the investment behaviour of different agents in a simplified way. Perfect information on future prices and costs cannot be expected, and investments in energy crop production or renewable energy plants might be perceived as riskier than continuing standard crop rotation or investing in fossil fuel plants. An extra premium (both reflecting risk aversion and the benefit of waiting for new information) to engage in energy crop cultivation as well as investment in new technologies can be expected, at least before the crops/technologies are established, and there is a widespread acceptance of CO_2 reduction policies. See Dixit and Pindyck (1993) and Parks (1995) for a thorough discussion of how uncertainty and risk affect investment decisions. Other factors

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[6] Data in these two sources differ, and an apparent difference between the elasticities for the different food product categories used in our model cannot be obtained.

not taken into account but relevant to investment decisions are liquidity constraints, transaction costs and lack of knowledge of investment opportunities. Further, endogenous technical change is not included in the analysis.

Environmental constraints on intensified food production (e.g., eutrophication, salinization and reduced soil organic matter[7]) and climatic change effects (e.g., precipitation and temperature changes) on agriculture are not included in the analysis, neither is the plausible price increase of agriculture inputs, as a result of increased energy prices. For high carbon prices, these price increases as estimated by Peters et al. (2001) are relatively small compared to our estimates of the increase in food commodity prices as a result of the land use competition.

The U.S. agricultural sector is influenced by public subsidies and other market-distorting policies. These policies are not included in the model. The future of these policies is uncertain. Further, the main focus of this paper is not to predict the future of the U.S., but rather to analyze the phenomenon of land use competition itself and improve ways to model it. For these reasons, and because subsidies distort the underlying economic mechanisms we want to study, we have chosen not to include these policies in the model.

We neglect the possibility of afforestation on agricultural land. The main reason is that we want to focus on the food-fuel competition. Studies have shown (Lee et al. 2005; Hedenus and Azar 2005) that afforestation is likely to be as important a carbon control option as production of bioenergy when carbon prices are relatively low. However, when the price of carbon increases, bioenergy becomes a more cost-effective option for reducing carbon emissions (Lee et al. 2005; Hedenus and Azar 2005). For this reason, and because the potential contribution from carbon sinks toward solving the climate problem is rather low,[8] and since our focus is the interaction between the energy and the agricultural system, the omission of afforestation should not negatively affect our results.

We have excluded the forestry sector, except for forest residues and mill residues, which we assume to be constant during the time modeled. The reason for this is that the growth of biomass on timberland in 1997 was about about 330 million ton (about 6.6 EJ), (Forest Service 2001), whereas the total use of bioenergy in the model after 2050 is about 40 EJ per year. That is, the biomass flows in the forest sector is rather small compared to the use in the energy sector. One possible caveat here is that higher energy prices may make it interesting to start fertilizing forests, see Börjesson et al. (1997).

It would be interesting to analyze the potential competition between wood products (timber and pulpwood) and bioenergy. This competition has already started to take place in Sweden for pulpwood. But that is beyond the scope of this paper.

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[7] Concerning soil organic matter and the related opportunity of increasing the carbon stock in soils, McCarl and Schneider (2001) have shown that this mitigation option is likely to be a cost-effective abatement option for low carbon prices, but that it becomes less important for high carbon prices. Further, the mitigation potential of increasing soil carbon stock is limited. A study by Sperow et al. (2003) estimated the U.S. potential to be approximately 80 Mt/yr, i.e., about 5% of the US annual CO_2 emissions today.

[8] For example, let us assume that all grazing areas, both pasture and range, in the U.S. are used for carbon sinks and that the carbon stock in mature forests is 100 ton carbon per hectare. Then the total storage capacity would be about 25 billion tons of carbon, i.e., 10% of the estimated cumulative baseline emissions between 1990 and 2100.

3 Scenario assumptions

The model is run until the year 2130, and we report results until 2100. Scenarios for GDP, energy demand, fossil fuel supply, nuclear energy, trade and population are assumed as inputs to the model.[9] The assumptions are:

- The demand for each food category is assumed to be constant on a per capita basis as long as the prices remain constant. If prices go up or down the demand will either go down or up respectively, as determined by the price inelastic demand.
- Energy demand under constant prices will grow in accordance with GDP but with an autonomous energy efficiency improvement (AEEI) of 0.7% per year. Other models have assumed a similar value; in the MIT-EPPA model a median value of 0.96 % per year is assumed (Webster et al. (2002)), and Azar and Dowlatabadi (1999) report that that the AEEI is usually specified between 0.5 and 1.0% per year. Further reductions take place if the price of energy increases as a result of the demand function.
- The GDP/capita is assumed to grow to about US$ 75 000 per year by 2100. This is lower than in Manne and Richels (2004) and higher than in Nordhaus (2004).
- The trade in agricultural products is assumed to be constant over the modeling time horizon at a level equal to the present export minus import. Studies where bioenergy is not considered either assume or conclude that the net export increases over the coming decades, Rosegrant et al. (2001)); USDA (2003). The constant net export of agricultural products assumption is tested in the sensitivity analysis.
- Trade in fossil fuels is dealt with implicitly. We assume the U.S. can use as much oil and natural gas as is used by North America in the IIASA/WEC (1998) scenario B. This approach simulates increased scarcity rents in a very simplified way. We do not consider any upper limit on coal supply.
- Two scenarios are presented: a “reference scenario” without carbon abatement policies and a “climate policy scenario” with a stringent carbon abatement policy. We assume that a carbon price of US$ 50/tC is introduced, either through a tax or a cap and trade system, in 2010, and that it subsequently grows by 3%/yr until it reaches US$ 800/tC by 2100. It is unlikely that such a carbon price will be implemented in the U.S. by the year 2010, but the purpose of this exercise is not to predict what the U.S. energy and agricultural systems will look like, but to examine how these two sectors might co-evolve, if a stringent carbon abatement policy is introduced.
- The population reaches 570 million by 2100, as compared to 284 million people in 2000 (US Census Bureau, 2000).
- Nuclear power is constrained upward at its currently installed capacity.

4 Results

4.1 Energy supply structures

In the reference scenario, the energy supply is dominated by coal, and the total primary energy supply reaches 240 EJ/year by 2100. These results for the primary energy supply are roughly in line with scenarios in the Annual Energy Outlook, EIA (2003). However, our

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[9] Important to remember is that the results should not be interpreted as a prediction of a likely situation in the U.S., but as an illustration of possible price changes and the interaction between the energy and agricultural systems if stringent CO_2 constraints are introduced.

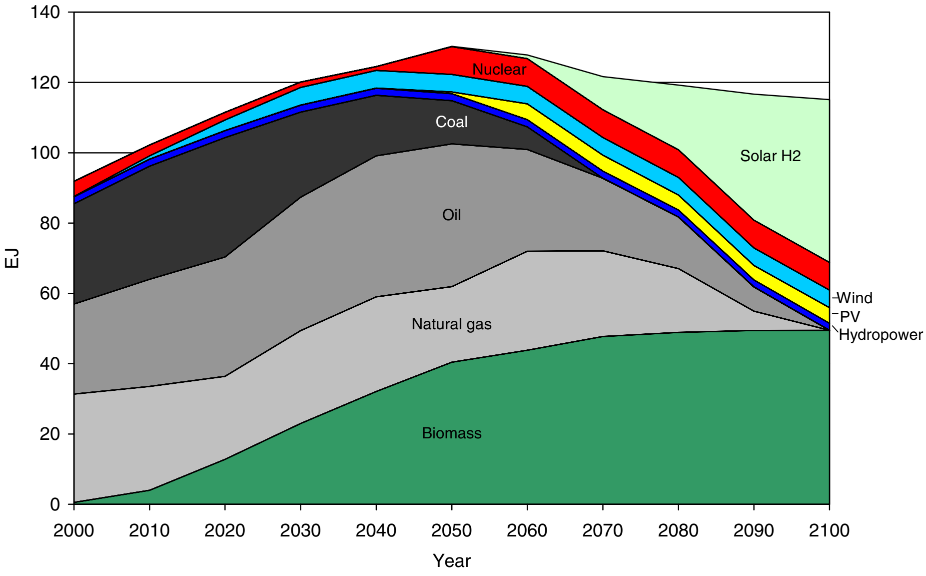

Fig. 2 The supply of energy sources in the climate policy scenario

scenario relies more on coal and less on natural gas and oil. In the climate policy scenario, the increased carbon prices make fossil fuels increasingly expensive and they lose market shares, see Fig. 2. This is especially significant for coal, which is completely phased out by 2070 in the climate policy scenario (carbon capture and storage is not an available option in the base case run of this scenario). As a result, the use of renewable energy sources, including bioenergy, increases. Energy supply in the year 2050 is approximately 50 EJ

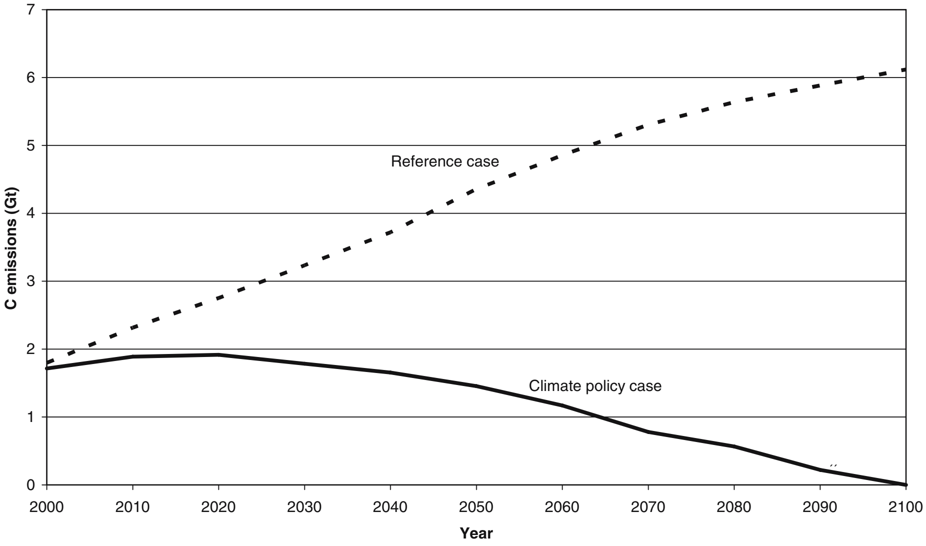

Fig. 3 Carbon emissions in the reference and climate policy scenarios

lower in the climate policy scenario than in the reference scenario. This is mainly due to the use of price responsive demand functions and higher energy prices.

The bioenergy sources currently in use in the U.S. are mainly wood residues for heat and electricity (in reality about 0.2 EJ/year of ethanol from corn is also used but it is driven by subsidies that are not considered in the model). As the carbon tax increases, bioenergy grows in importance. The main part of the bioenergy is used for heat production (residential and industrial heat), and no bioenergy enters the transportation sector, for cost-effectiveness reasons, see Azar et al. (2003).

4.2 Carbon emissions

The simulated emissions in 2000 are about 1,700 Mt C. In the climate policy scenario, emissions fall continuously from 2020 and almost reach zero by 2100, see Fig. 3.

4.3 Land use patterns

In the reference scenario, no bioenergy plantations are established and the areas of cropland and grazing land remain roughly constant at their year 2000 values. In the climate policy scenario, bioenergy plantations are established on cropland in 2010 when the carbon price is US$ 50/tC (Fig. 4). In subsequent decades energy crop plantations expand simultaneously on grazing land and cropland, even though non-land costs are significantly higher for energy crops cultivated on grazing land. The lower opportunity cost of grazing land compared to cropland makes this expansion cost-effective. The exogenous constraint on the amount of grazing land that can be used for energy crop plantations sets in three decades after the introduction of energy crops (we set the constraint to 48 Mha see Section 2.2). See Sections 5.3.1 and 5.3.2 for a detailed sensitivity analysis.

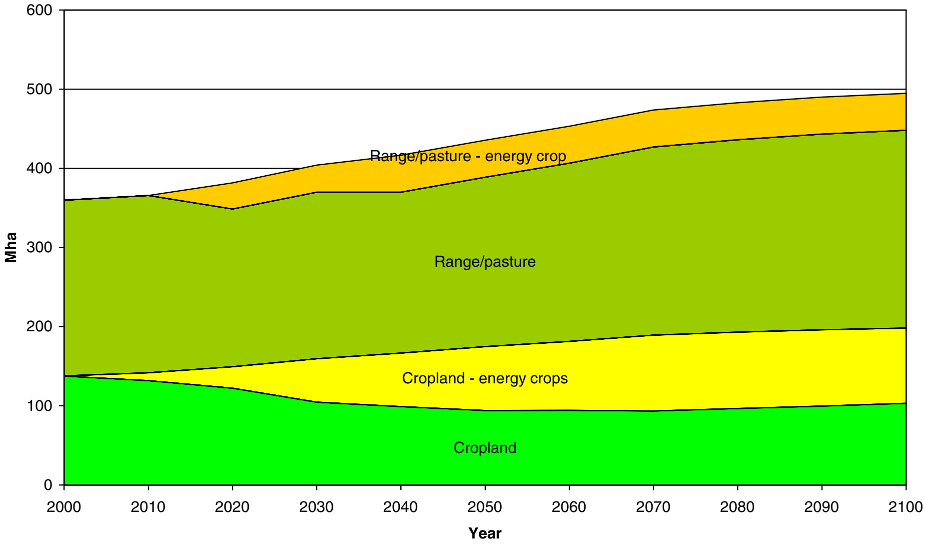

Fig. 4 Land use in the climate policy scenario

The introduction of energy crops on former grazing land results in an increased demand for concentrates and hay for cattle production. This results in more industrial forms of cattle production.

4.4 Land rent development

In the reference scenario, the rental value of cropland remains roughly constant over the first 50 years and then increases slightly. In the climate policy scenario the demand for bioenergy grows, resulting in competition for land and eventually higher land rents. This is illustrated in Fig. 5, where the country average rental value of cropland increases by a factor of ten.

The rental value increase for grazing land is also significant in the climate policy scenario, but not as high as that for cropland. In particular, there is a shadow price (a country average about US$ 80 per ha (current value) in the year 2050) associated with the constraint on the amount of grazing land that can be used for bioenergy. This shadow price suggests there is a strong demand for bioenergy from low-quality land despite the fact that yields are roughly 30% lower than on cropland.

4.5 Farm gate price development

In the reference scenario, cereal prices decrease somewhat until 2050 and then increase gradually up to about US$ 140 per dry ton by 2100, see Fig. 6. This price development is a result of the assumption that the productivity growth in the crop and animal sectors outstrips the population growth prior to 2050. In the climate policy scenario, the carbon price leads to higher energy prices which lead to higher profitability in energy crop production. In order to satisfy food demand, food prices increase in the model. If not, energy crop cultivation would appropriate an even larger area. In 2050, wheat prices are

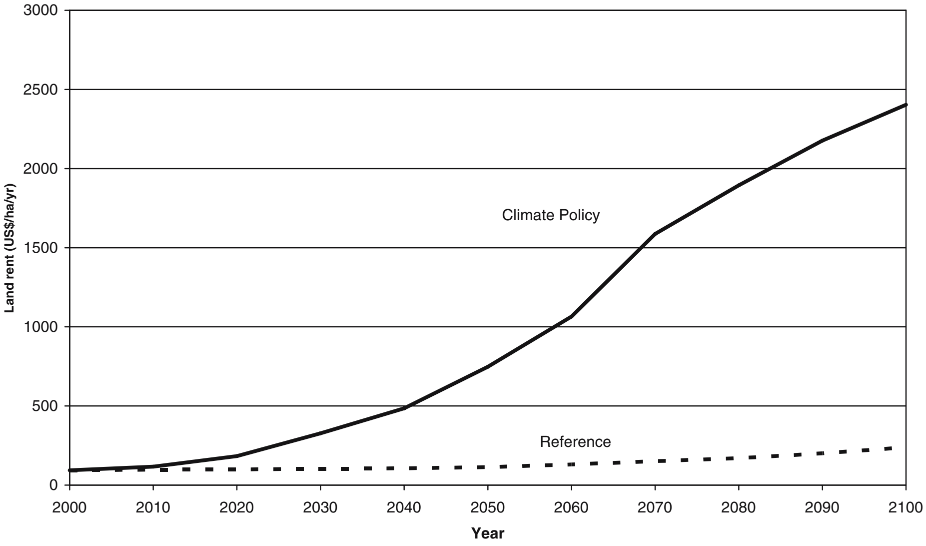

Fig. 5 Land rent in the reference and climate policy scenarios

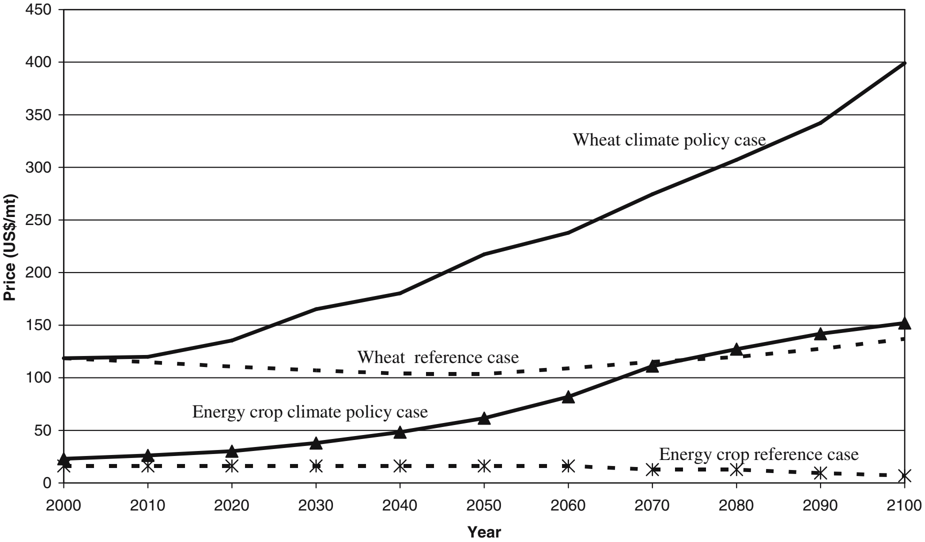

Fig. 6 Farm gate price development for cereals and energy crops in the reference and the cimate policy scenarios

about US$ 215 per ton compared to US$ 105 per ton in the reference scenario, see Fig. 6. In 2100, the wheat price reaches close to US$ 400 per ton in the climate policy scenario, compared to US$ 140 per ton in the reference scenario. The relative price increase for other crops and animal products is in general somewhat lower than the price increase for wheat (55–110% for food crops and 20–30% for animal products by 2050).

As can be seen in Fig. 6, the bioenergy price is even more sensitive, in relative terms, to the carbon price than is the wheat price.

Although the carbon price heavily influences farm gate prices for agriculture products, demand is less affected, on the order of a few percent for all food products. The farm gate price is a minor part of the retail price, and demand elasticities are low in wealthy countries like the U.S.

5 Sensitivity analysis

We performed a detailed sensitivity analysis to assess the robustness of the results regarding the key questions about food price impacts and where biomass plantations are established.

5.1 A Monte Carlo analysis of future prices

To assess the sensitivity of our results regarding food prices, we performed a Monte Carlo analysis where several critical and uncertain parameters are varied simultaneously. The parameters included in the analysis are AEEI, cost of hydrogen technologies, maximum cumulative oil supply, maximum cumulative natural gas supply, exogenous yield growth, exogenous animal productivity growth, ESUB, land supply elasticity, share of produced crop residues available as bioenergy and the exogenously-set net export of agricultural commodities. These parameters, except the net export, are varied randomly in the range +/− 50 %, with independent uniform probability functions. For the exogenously-set net export of agricultural commodities, we assume a randomly-varied linear trend (using a uniform probability function), in which the net export by 2100 is somewhere between twice the base case assumption and zero.

The Monte Carlo analysis is performed for three settings:

1. Climate policy case with the same emission trajectory as in the climate policy base, i.e. the trajectory presented in Fig. 3.
2. Climate policy case with CCS, with the same emission trajectory as in setting 1.
3. Reference case, no emission constraints.

One hundred runs were performed for each setting.

As seen in Fig. 7, our results presented in Section 4.5 are valid in the sense that carbon prices and the subsequent expansion of bioenergy affect food prices under a wide range of parameter input assumptions. The ratio between the wheat price in the climate policy case and the price in the reference case in 2050 lies in the range 1.5 up to 3.5. Analysis of the results reveals that the ratio is especially sensitive to changes in two parameters, namely, elasticity of substitution (ESUB) between land and other production inputs in crop production and supply elasticity of land.

We also performed the Monte Carlo analysis with Carbon Capture and Sequestration (CCS) as a mitigation option. The analysis showed that the increase in the wheat price ratios is in general lower, by roughly 30%, when CCS is an option. However, as in the climate policy base case, when the targets get stricter, the use of bioenergy increases, which leads to greater land scarcity and higher food commodity prices.

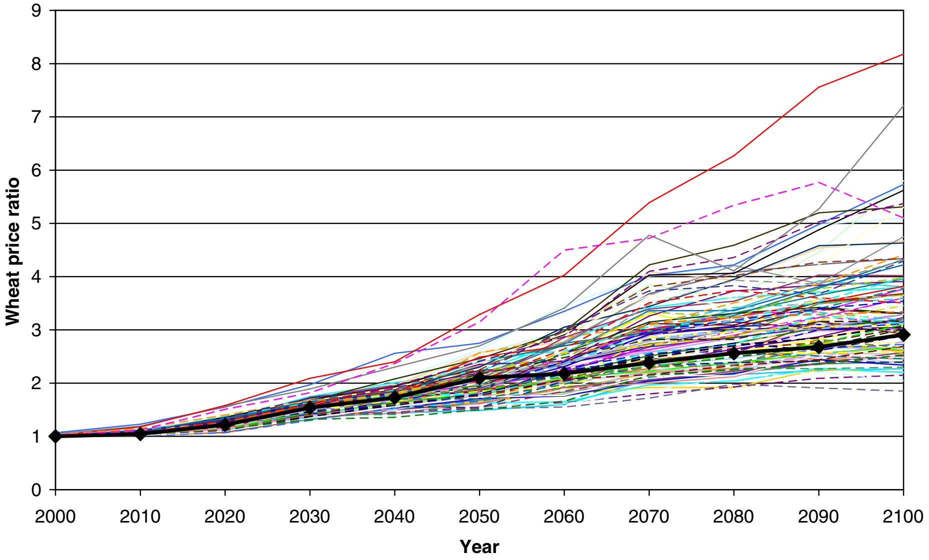

Fig. 7 The ratio between wheat prices in cases with and without climate policies. Each line represents the ratio for a specific parameter combination. The *thick black line with diamonds* shows the ratio for the base case without CCS

5.2 Supply elasticity of land

In the base case, we assumed a land supply elasticity of 0.1, see Section 2.2. Here, we assess how a high elasticity of 0.3 and a low elasticity of 0.03 affect wheat prices in the climate policy case.

We find that the wheat prices are roughly 25% lower by 2050 and 30% lower by 2100 and 10% higher by 2050 and 80% higher by 2100 for the high and low supply elasticity case, respectively, as compared to our base case climate policy case.

With an elasticity of 0.03, the agricultural land area remains close to constant over the whole modelling time horizon, even in the climate policy case. However, with an elasticity of 0.3, the agricultural land area increases more than 200 Mha in the climate policy case, but only slightly in the reference case. In reality, both physical and biological constraints would prevent an expansion of 200 Mha. Thus, the higher values for the supply elasticity may be reasonable for modelling individual crops for limited price ranges, but not for modelling a large of all cropland (see also Section 2.2).

5.3 Biomass supply from low-quality land

The second key question in our paper concerns whether cropland or grazing land will be targeted for energy crops. Land with low energy crop yields is not likely to be profitable under current conditions. However, in the long run, if carbon prices are high, low-yielding land might become profitable for energy crop production; see e.g. Hoogwijk et al. (2005). Here we test the sensitivity of our results with respect to assumptions about the possibility to grow energy crops on low-quality land.

5.3.1 Energy crops on poor land

We have tested a broad range of yields on poor grazing land[10] assuming that roughly a third of the grazing land not suitable for energy crop production (in total 70 Mha) in our base case can be utilized for energy crop production.

In Fig. 8, the amount of low-quality grazing land devoted to energy crop production is shown as a function of the relative yield of energy crops on this land, as compared to on cropland. It can be seen that energy crops are established over large areas of grazing land, even if the yield is assumed to be only 30–50% of what one would obtain on cropland. The reason behind this expansion of costly bioenergy is that the alternative energy sources needed to achieve the emission targets, e.g. solar energy converted into hydrogen, are even more expensive.

5.3.2 Expansion of energy crops

To analyze at what carbon prices energy crop cultivation begins in the different land classes, we ran the model for a range of constant carbon prices from 2010 on. As above, the high-yielding grazing land that can be used for energy crop production is constrained to

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[10] In reality, one has to assess the fragility of these lands and how an energy crop expansion would affect ecosystems, soil carbon and the long-term productivity. Two reviewers of the first version of this paper had strong reactions to our assumptions concerning cultivation of energy crops on rangelands, i.e. poor grazing lands. One of the reviewers considered this to be “completely flawed,” while the other reviewer thought that we were too conservative in our estimates.

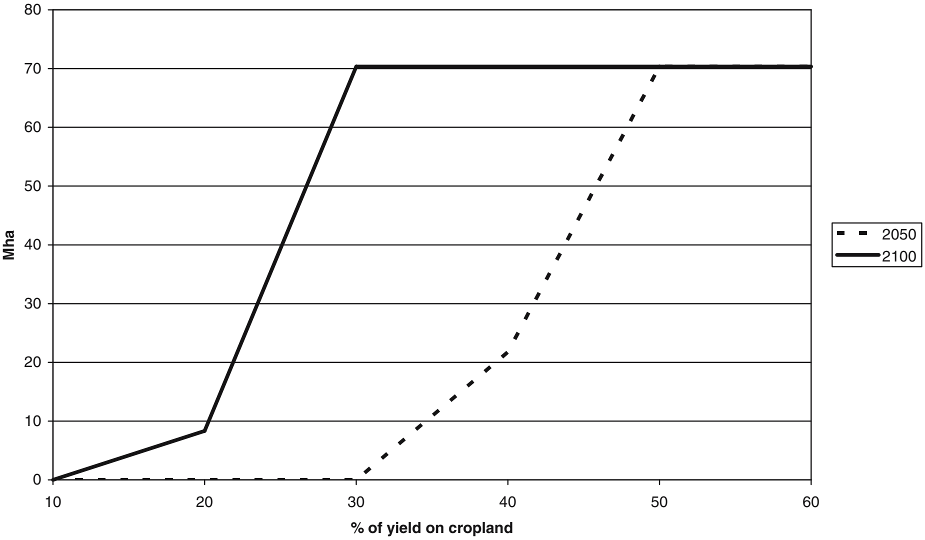

Fig. 8 Use of grazing land for energy crop production as a function of the relative yield of energy crops on grazing land

48 Mha, while the low-yielding grazing land that can be used for energy crop production is constrained to 70 Mha. As is seen in Fig. 9, in 2030, at low carbon prices (about US$ 20/t C), only cropland is used for energy crop cultivation; at carbon prices above US$ 40/t C, energy crops are introduced on high-yielding grazing land. For cultivation of energy crops on low-yielding grazing land (yields assumed to be 40 % of those on cropland in the same region), carbon prices have to reach above US$ 150/t C.

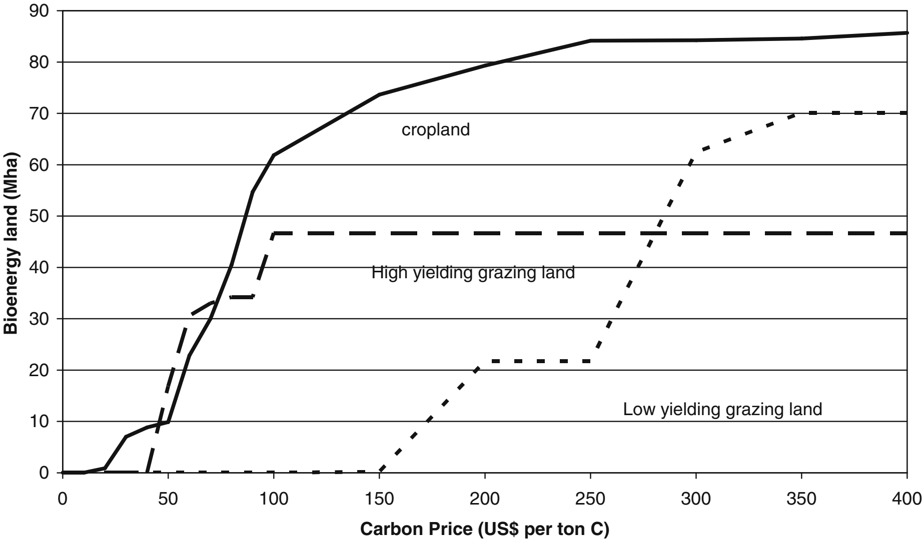

Fig. 9 Energy crop area for three different land classes as a function of the carbon price in 2030

Note that in general most of the bioenergy actually comes from cropland, even though the area of grazing land devoted to energy crop cultivation is larger. The reason is the higher yields achieved on cropland.

Further, cereal prices are roughly unaffected by the assumption of the yields on low-quality land. Somewhat paradoxically, under some parameter combinations (low relative yields on the low-quality land), an expansion of energy crops on low-quality land can lead to a *slight* increase in the wheat prices (compare to a case where bioenergy on low quality lands is prohibited). The mechanism behind this is that feed obtained from grassland previously used for grazing must instead be supplied from other sources.

6 Conclusions

We have analyzed the impact of stringent CO_2 abatement policies on food prices and where it is most cost-effective to cultivate energy crops, on cropland, or on low-quality land, grazing land.

The analysis was carried out with the use of a non-linear optimization model (LUCEA), developed specifically for the purpose of this project. We constructed a reference scenario without any carbon abatement as well as a climate policy scenario in which emissions drop toward zero by the end of the century.

Our main results and conclusions can be summarized as follows:

- Farm gate prices for all crops as well as animal products increase substantially. We have focused especially on wheat and conclude that in the climate policy scenario, the wheat price could be double, or even higher, than in the reference case with no carbon abatement, from 2050 on. These results are similar to results obtained by McCarl and Schneider (2001); Schneider and McCarl (2003); Azar and Berndes (1999); and Azar (2005).
- A Monte Carlo analysis showed that the simulated wheat price was 50–200% higher in 2050 in the climate policy case as compared to the reference case. Thus, our conclusion that food prices increase significantly seems robust, but the exact level of increase is of course uncertain.
- However, the increase in food commodity prices does not cause any major shift in food consumption patterns since the food price elasticity is low and the farmgate price is small relative to the retail price.
- We find that when carbon taxes are low (US$20/t C), bioenergy is primarily allocated on cropland. For higher carbon taxes, plantations are also established on high-yielding grazing land. For even higher carbon prices, plantations are established on low-yielding grazing land, if this possibility is included in the analysis.
- The reason behind the expansion of energy crops on grazing land is that the opportunity cost of prime cropland increases due to the food-fuel competition. Owing to this increase, it becomes cost-effective to expand bioenergy plantations on non-cropland even though non-land costs are higher on this land.[11] Had it not been for the fact that food demand is so price-inelastic and land so costly to substitute in the production of food and feed, more

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[11] It may be noted that the expansion of plantations on grazing lands seemingly contradicts Azar and Larson (2000), but it should be kept in mind that their analysis did not consider food demand and, more importantly, did not consider very stringent climate policies.

plantations would have ended up on cropland and the introduction of energy crops on grazing land would have been postponed.

- It is important, though, to note that under market conditions, this allocation of bioenergy plantations to low-quality land (grazing land) does not take place in the absence of the food-fuel competition, but rather as a result of that competition.
- Assuming a larger potential area of grazing land suitable for energy crop production results in a larger appropriation of grazing land for energy crop production and somewhat less energy crop production on cropland. The reason behind this is that assuming a larger area of grazing land suitable for energy crop production results in a larger supply of energy crops for a given biomass price above the production cost on this grazing land. Thus, in the model the price for energy crops in a given period would just be slightly lower, giving a small reduction in the amount of cropland used for energy crops.

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Appendix A

Model Specification

The model specified below characterise the essence of the LUCEA model.

Sets

A	Containing elements a ($a \in A$) of final consumption goods and services (*milk, cattle meat, other animal products, wheat, maize, soybean, electricity, heat, transport*).
$B \subset A$	Containing elements a ($a \in B$) of consumable food products (*milk, cattle meat, other animal products, wheat, maize, soybean*).
$C \subset B$	Containing elements a ($a \in C$) of consumable animal food products (*milk, cattle meat, other animal products*).
$D \subset A$	Containing elements a ($a \in D$) of consumable energy carriers (*electricity, heat, transport*).
E	Containing elements e ($e \in E$) of primary agricultural products (*hay, wheat, maize, soybean, grass, energy crops*).
$V \subset E$	Containing elements e ($e \in V$) of agricultural products used as feed (*hay, wheat, maize, soybean, grass*).
F	Containing elements f ($f \in F$) of land classes (*cropland, grazing land*).
J	Containing elements j ($j \in J$) of regions (*Appalachian, Corn belt, Delta states, Northeast, Lake states, Mountain, Pacific, Southern plains, Northern plains, Southeast*).
N	Containing elements n ($n \in N$) of energy sources (*oil, coal, natural gas, uranium, bioenergy, hydro, solar-direct, solar-*H_2*, wind*).
$H \subset N$	Containing elements of n ($n \in H$) of exhaustible primary energy sources (*oil, coal, natural gas, uranium*).

$G \subset N$	Containing elements of n ($n \in G$) of renewable energy sources (*bioenergy, hydro, solar-direct, solar-H_2, wind*).
$X \subset N$	Containing elements of n ($n \in X$) of intermittent energy resources (*solar-direct, wind*).
R	Containing elements of r ($r \in R$) of production strategies for cattle meat and milk (*range, mixed, industrial*).
T	Containing elements of t ($t \in T$) of time indices (*2000, 2010, 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100, 2110, 2120, 2130*).

Variables

U_t	Integral of the inverse demand function
$S_{e,f,j,t}$	Primary crops and grasses produced per annum
$Q_{f,j,t}$	Consumable products and energy carriers consumed per annum
$M_{a,t}$	Primary meat products produced per annum
$L_{f,j,t}$	Total land area in each region and land class cultivated per annum
$P_{e,f,j,t}$	Total land in each region and land class cultivated with a specific primary agricultural product per annum
$K_{a,n,t}$	Energy conversion capital stock
$I_{a,n,t}$	Investments in new energy conversion capital
$O_{f,j,t}$	Annual land supply cost
$Y_{e,f,j,t}$	Other inputs in primary agricultural production
Z_t	Total cost of energy investments, fuel costs, carbon dioxide taxes, transport equipment costs, agricultural input costs, land supply costs, and other agricultural production related costs
W	Objective function, the net present value of social payoff
$EP_{a,n,t}$	Supply of primary energy
$ES_{a,n,t}$	Supply of secondary energy
$MP_{a,r,t}$	Animal product production costs minus feed costs
BR_t	Amount of residues used as bioenergy
$SF_{e,f,j,t}$	Crops and grasses used as feed in animal product production
$SV_{e,f,j,t}$	Crops used for production of vegetable products

Parameters

τ_t	Carbon tax
χ_n	Primary energy cost
$\iota_{a,n}$	Unit investment cost for energy conversion technologies
$\alpha_{e,f,j,t}$	Calibration constant for the CES function describing primary agricultural production
$\zeta_{e,f,j,t}$	Calibration constant for the CES function describing primary agricultural production
σ_e	Elasticity of substitution between land and other inputs in primary agricultural production
θ	Land supply elasticity
$\omega_{f,j}$	Inverse land supply cost function calibration constant
γ	Demand elasticity
β_a	Inverse demand function calibration constant

ν_a	Transport, equipment, retail and storage costs for final consumption of products and energy carriers
ρ	Discount rate
Π_n	Total cumulative supply limit of non-renewable energy resources
$\Lambda_{n,t}$	Total annual supply limit of renewable energy sources
$\delta_{a,n}$	Depreciation rate of energy conversion capital stock
ϖ	Maximum annual increases in energy conversion capital stock
Δ	Years per decade, typically ten
$\psi_{r,e}$	Share of feed in animal product production strategy
$\upsilon_{j,t}$	Maximum amount of grazing land that can be used for bioenergy
η_n	Carbon emissions per unit energy
φ	Limit of the relative share of how much of the electricity production that can be supplied from intermittent sources
κ_e	Factor that sets the limit of how much of the residues from primary crops that can be used as bioenergy
λ	Unit cost of using agricultural residues as bioenergy
ξ_e	Conversion efficiency of feed intake to edible animal product
μ_r	Calibration constant used in the animal product supply function
$\varepsilon_{a,n}$	Energy conversion efficiency

Equations

Objective function Maximization of net present value of net social payoff, calculated as the area under the inverse demand curve minus the supply costs.

$$\text{Max } W = \sum_{t \in T} \frac{U_t - Z_t}{(1+\rho)^{t-2000}} \tag{1}$$

Total cost function Sum of total supply costs in current value.

$$Z_t = \sum_{a \in D,\, n \in N} \iota_{a,n} \cdot I_{a,n,t} + \sum_{f \in F, j \in J} O_{f,j,t} + \sum_{e \in E, f \in F, j \in J} Y_{e,f,j,t} + \sum_{n \in N} (\chi_n + \tau_t \cdot \eta_n) ES_{n,t}$$
$$+ \sum_{a \in A} \nu_a \cdot Q_{a,t} + \sum_{a \in C,\, r \in R} MP_{a,r,t} + \lambda \cdot BR_t, \forall t \in T \tag{2}$$

Integral of the inverse demand function Derivation of the area under the demand curve, obtained by integrating the inverse demand function.

$$U_t = \sum_{a \in A} \int_0^{Q_{a,t}} \beta_a \cdot \widehat{Q}_{a,t}^{\frac{1}{\gamma}} d\widehat{Q}_{a,t}, \forall t \in T \tag{3}$$

Market clearing condition for energy carriers Condition that ensures that demand is less than the supply of energy carriers.

$$Q_{a,t} \leq \sum_{n \in N} ES_{a,n,t},\ \forall t \in T,\ \forall a \in D \tag{4}$$

Market clearing condition for vegetable food products Condition that ensures that demand is less than the supply of each vegetable food product.

$$Q_{a,t} \leq \sum_{j \in J} SV_{e,cropland,j,t}, \forall a, e \in E \cap B, \forall t \in T \tag{5}$$

Market clearing condition for animal food products Condition that ensures that demand is less than the supply of each animal food product.

$$Q_{a,t} \leq M_{a,t}, \forall a \in C, t \in T \tag{6}$$

Market clearing condition for land in each region Condition that ensures that the land used in each region and in each land class is less than the supply of land in each land class and region.

$$L_{f,j,t} \leq \sum_{e \in E} P_{e,f,j,t}, \ \forall f \in F, \ \forall j \in J, \ \forall t \in T \tag{7}$$

Primary agricultural production function Constant Elasticity of Substitution function used to simulate the annual harvest of each primary agricultural product in each region.

$$S_{e,f,j,t} = \left(\alpha_{e,f,j,t} \cdot Y_{e,f,j,t}^{\frac{1}{1-\sigma_e}} + \zeta_{e,f,j,t} \cdot P_{e,f,j,t}^{\frac{1}{1-\sigma_e}}\right)^{1-\sigma_e}, \forall e \in E, \forall f \in F, \forall j \in J, \forall t \in T \tag{8}$$

Supply balance condition Condition that ensure that the supply of primary crop and grasses production exceeds the crop and grass supply to production of animal products and vegetable products

$$S_{e,f,j,t} \geq SF_{e,f,j,t} + SV_{e,f,j,t}, \forall e \in E, \forall f \in F, \forall j \in J, \forall t \in T \tag{9}$$

Land Supply cost Derivation of land supply cost. The total cost is obtained by integrating the inverse supply function.

$$O_{f,j,t} = \int_{0}^{L_{f,j,t}} \omega_{f,j} \cdot \widehat{L}_{f,j,t}^{\frac{1}{\theta}} d\widehat{L}_{f,j,t} \forall f \in F, \forall j \in J, \forall t \in T \tag{10}$$

Animal product supply function Nested structure to simulate animal product supply. Summation of separate Leontief functions for each animal product production strategy. Each Leontief function is a function of production capital ($MP_{a,r,t}$) and a linear (convex) combination of different feed.

$$M_{a,t} = \sum_{r \in R} \mathrm{Min}\left[\sum_{e \in V}\left(\xi_e \cdot \psi_{r,e} \cdot \sum_{f \in F, j \in J} SF_{e,f,j,t}\right), \mu_r \cdot MP_{a,r,t}\right], \forall a \in C, \forall t \in T \tag{11}$$

Maximum land that can be used for bioenergy The maximum amount of grazing land that can be used to cultivate energy crops in each region.

$$P_{energycrops,\,grazingland,\,j,\,t} \leq \upsilon_{j,\,t} \forall j \in J, \forall t \in T \tag{12}$$

Residue production available as bioenergy Constraint that determines the maximum supply of crop residues available as bioenergy.

$$BR_t \leq \sum_{e \in E, f \in F, j \in J} \kappa_e \cdot S_{e,f,\,j,\,t}, \forall e \in E, \forall f \in F, \forall j \in J, \forall t \in T \tag{13}$$

Energy conversion stock equation State equation for the capital stock of energy conversion technologies.

$$K_{a,n,t} = K_{a,n,t} \cdot \left(1 - \delta_{a,n}\right)^{\Delta} + \Delta \cdot I_{a,n,t}, \forall n \in N, \forall t \in T, \forall a \in D \tag{14}$$

Secondary energy supply function (leontief function) Leontief function used to simulate secondary energy supply, i.e. energy conversion efficiency is a fixed value for each secondary energy supply sector.

$$ES_{a,\,n,\,t} \leq \varepsilon_{a,\,n} \cdot \mathrm{Min}\left[EP_{a,\,n,\,t}, K_{a,\,n,\,t}\right], \forall n \in N, \forall t \in T, \forall a \in D \tag{15}$$

Maximum growth constraint on energy technologies Constraint that determines the upper rate at which the different energy conversion technologies can grow.

$$K_{a,\,n,\,t+1} \leq K_{a,\,n,\,t} \cdot (1 + \varpi)^{\Delta}, \forall n \in N, \forall t \in T, \forall a \in D \tag{16}$$

Intermittency constraint on electricity production Constraint that limits the use of intermittent energy sources.

$$\sum_{n \in X} ES_{electrcity,\,n,\,t} \leq \phi \cdot \sum_{n \in N} ES_{electricity,\,n,\,t}, \forall t \in T \tag{17}$$

Renewable energy supply constraint (annual constraint) Constraint that limits the annual supply of renewable energy categories (except for bioenergy, i.e. $\Lambda_{\mathrm{bioenergy}}$=infinity).

$$\sum_{a \in D} EP_{a,\,n,\,t} \leq \Lambda_{n,\,t}, \forall n \in G, \forall t \in T \tag{18}$$

Market clearing condition for bioenergy Condition that ensures that the demand is less than the supply of bioenergy.

$$\sum_{a \in D} EP_{a,\,bioenergy,\,t} \leq BR_t + \sum_{f \in F, j \in J} S_{energycrops,f,j,\,t}, \forall n \in G, \forall t \in T \tag{19}$$

Nonrenewable energy supply constraint (stock constraint) Constraint limits the cumulative supply of nonrenewable energy sources.

$$\sum_{a \in D, t \in T} EP_{a,n,t} \leq \frac{\Pi_n}{\Delta}, \forall n \in H \tag{20}$$

Appendix B

Calibration and data sources

The model has been calibrated to represent the agricultural system for the first half of the 1990s. The data is estimated from various sources. However, due to lack of data for some categories, mainly grazing land, the estimates have to be considered to be rather crude.

Land areas are estimated from Vesterby and Krupa (2001), and NRCS (2000). The maximum land suitable for energy crops is primarily estimated from de la Torre Ugarte et al. (2000), Graham (1994), and Graham et al. (1996). We assume that all cropland can be used for energy crop cultivation. We estimate from data in Graham (1994) and de la Torre Ugarte et al. (2000) that about 47 Mha of grazing land (including cropland pasture) can be used for energy crop production.

Assumptions regarding energy crop yields are from de la Torre Ugarte et al. (2000). The energy crop yield on grazing land is assumed to be approximately 70% of those on cropland in the same region, somewhat lower than what is assumed in Downing and Graham (1996). Grass yields achieved on grazing land are estimated from Joyce (1989). Costs of production for food and feed crops are taken from ERS (2002a), while the cost of managing grazing land is estimated from Lubowski (2002), Torell et al. (1986) and Van Tassell et al. (1997). Crop yields are calculated by dividing the total production of each crop with the area dedicated to the crop in the same production region. Maize in our model represents costs and yields for feed grains, while soybean in our model represents costs and yields for oil crops. The cost of production for energy crops comes from Walsh et al. (2000). The non-land cost of production for energy crops is equal on a per hectare basis for cropland and grazing land, as assumed in Azar and Larson (2000).

The cropland area dedicated to cotton, fruit and other crops not included in the analysis adds up to about 15 million ha/year. This area is assumed to stay constant through our modeling time horizon. Cropland that currently is idled is assumed being included through the use of a land supply function, i.e. more land is brought into production when the land rental values increases.

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