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ORIGINAL ARTICLE

# Impact of bioenergy crops in a carbon dioxide constrained world: an application of the MiniCAM energy-agriculture and land use model

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**Abstract** In the coming century, modern bioenergy crops have the potential to play a crucial role in the global energy mix, especially under policies to reduce carbon dioxide emissions as proposed by many in the international community. Previous studies have not fully addressed many of the dynamic interactions and effects of a policy-induced expansion of bioenergy crop production, particularly on crop yields and human food demand. This study combines an updated agriculture and land use (AgLU) model with a well-developed energy-economic model to provide an analysis of the effects of bioenergy crops on energy, agricultural and land use systems. The results indicate that carbon dioxide mitigation policies can stimulate a large production of bioenergy crops, dependent on the level of the policy. This production of bioenergy crops can lead to several impacts on the agriculture and land use system: decreases in forestland and unmanaged land, decreases in the average yield of food crops, increases in the prices of food crops, and decreases in the level of human demand of calories.

**Keywords** Bioenergy · Global energy scenarios · Climate change · Carbon dioxide · Integrated assessment

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## 1 Introduction

As policy-makers grapple with the issue of anthropogenic climate change caused primarily by emissions from the use of fossil fuels, they have proposed a turn to renewable and carbon-neutral energy sources to displace fossil fuels in the energy mix. Biomass energy crops present one such energy source, for the carbon dioxide ($CO_2$) emitted from the use of bioenergy crops is taken up by the growth of replacement crops.[1]

We examine here the impacts of an expansion of bioenergy crop production as induced by a $CO_2$ mitigation strategy. In order to be a viable energy source, bioenergy crops will have to successfully compete with other land uses for a share of a finite land resource. The extent to which bioenergy crops displace other land uses will influence global land use and the global agricultural system.

Past studies have begun to address this issue by estimating global bioenergy crop production potential, as in Fischer and Schrattenholzer (2001), and by beginning an examination of the dynamic effects of bioenergy on land use decisions, as in Yamamoto et al. (1999, 2000, 2001), Raneses et al. (1998), and Sands and Leimbach (2003). This paper extends the work of these past studies by using the MiniCAM integrated assessment model, which combines an updated version of the agriculture and land use (AgLU) model used in Sands and Leimbach (2003) with a well-developed energy model (Edmonds et al. 1997). This combination of a top–down energy-economic model with a nested land allocation mechanism provides enough detail to allow for analysis and interaction between key facets of the energy, agriculture and land use systems. We find that the global production of bioenergy crops, while helpful in obtaining desired $CO_2$ emission reductions for a lower cost, may have negative consequences on non-bioenergy agricultural production, agricultural yields and human caloric intake.

## 2 Model structure

### 2.1 AgLU model

The Agriculture and Land Use model was originally developed by Edmonds et al. (1996) as a complement to the MiniCAM to examine the dynamics of global land use change in response to a $CO_2$ mitigation policy. It has since been developed separately as a stand-alone model and considerably updated with improved calibration and land-use allocation mechanisms. Sands and Leimbach (2003) utilized this stand-alone version of the AgLU model along with the ICLIPS integrated assessment model to examine land use change $CO_2$ emissions.

The AgLU model is a top–down, partial equilibrium economic model with a base year of 1990 and 15-year time steps to 2095. It is designed as a partial equilibrium model to focus on markets that affect land use decisions. It is a global model reconfigured for this study into the 14 MiniCAM regions, as illustrated in Table 1.

[1] The production and transportation of bioenergy crops can produce $CO_2$ and nitrous oxide emissions. There might also be additional nitrous oxide emissions due to bioenergy crop fertilization. This study does not address these emissions.

**Table 1** The world regions used in MiniCAM

| Fourteen MiniCAM regions |
|---|
| United States |
| Canada |
| Latin America |
| Western Europe |
| Former Soviet Union |
| Eastern Europe |
| Africa |
| Middle East |
| Japan |
| Australia and New Zealand |
| South and East Asia |
| China and Centrally Planned Asia |
| Korea |
| India |

At the core of the model is a nested logit land allocation mechanism, described in detail in Sands and Leimbach (2003). This mechanism allows different land uses to compete on the basis of rate of return while also accounting for a finite land resource. Figure 1 shows the current nested structure. Land uses compete most directly with alternative uses within the same nest. For example, if more land is needed for grains, then land taken from other crops for the purpose of growing grains will have a higher yield than land taken from pastureland or forest, which would have a higher yield than land taken from the unmanaged land category.

The underlying mathematical structure of the land allocation mechanisms is based on the premise that there is a distribution of potential yields for each possible use of land. This distribution represents the yields that would be obtained if all land were allocated into that land use. This unobserved potential yield distribution is distinct from the actual distribution of yields, which reflects the results of competition between different land uses. Some land uses, such as certain food grains, occupy the high end of their unobserved potential yield distribution because only the highest yielding land is used. If the amount of land used for a given crop expands, the average productivity will tend to decline as production moves into land less suitable for that crop. Mathematically, this is conceptualized as a land use moving down its unobserved or “intrinsic” yield distribution. This decline in yield with crop expansion can be balanced by yield increases due to technological change (see Section 3.1), which includes changes in agricultural practices.

The nested structure assumes that the yield of each land use is correlated with other land uses within the same nest. Yields within each nest are correlated to a lesser extent with yields in higher nests. For example, there is considerable overlap in the highest yielding cropland for different crops, and a smaller degree of overlap between cropland and forestland (Fig. 1).

All land uses compete on the basis of rate of return, but yields, and hence, rates of return, will fall much more rapidly as net land use expands into other land uses not in the same nest. For instance, food grain crop yields will drop more significantly if food grain crops expand into forests than if they expand into coarse grain cropland. This structure is important for this study in that it reflects the fact that the highest yielding bioenergy cropland will overlap with some of the highest yielding traditional cropland (Berndes et al. 2001).

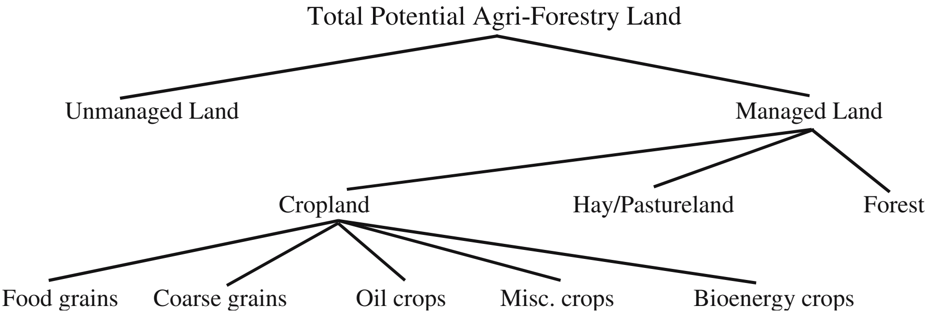



**Fig. 1** Land allocation nesting structure in AgLU

Through the intrinsic yield distribution, the land allocation mechanism implicitly includes spatial heterogeneities such as soil quality, climate and water constraints through the drop in yields as any land use expands into less suitable lands. Hence, it is designed to reflect the general heterogeneity of the land base. The intrinsic yield distribution can be interpreted as being represented by a Gumbel distribution, as described in Sands and Leimbach (2003). Intrinsic yield is different than average observed yield, which represents the actual yield obtained by the landowners. For an appropriate 1990 baseline, the observed yield and land use figures for each crop are calibrated to values for each region based on Food and Agriculture Organization of the United Nations (FAO) statistics (FAO 2001).

All land use data are aggregated from the FAO country level data. The nesting structure only considers potential agriculture and forestry land, which does not include urban land, parkland, alpine land, tundra, desert, and other unsuitable land for agriculture or forestry. Unsuitable lands are assumed to remain constant over time.

The AgLU model has global markets for forest products, forward forest products,[2] food grains, coarse grains, oil crops, miscellaneous crops, and bioenergy crops. In using global markets, international free trade is assumed. There are regional markets for ruminant animal products, allowing these to be derived from inputs of pasture and feed. The ratio of pasture and feed inputs is not fixed, but follows a constant elasticity of substitution production function based on the relative prices of pasture and feed. 1990 regional trade numbers for animal products are assumed to remain constant due to the relatively small amount of international trade in these products.

The demand for food grains, coarse grains, oil crops and miscellaneous crops is modeled as a function of the prices of the crops and the level of income, as elaborated on further in Sands and Leimbach (2003). The demand for processed crops, pork products and poultry products are separately calculated based on income and the production price of each of these products, which is, in turn, based on prices of the four input crops and the 1990 input ratios for each crop. Calibration data for all markets are also based on FAO statistics (FAO 2001).

[2] The market for forward forest products is the market for forest products 45 years from the current period.

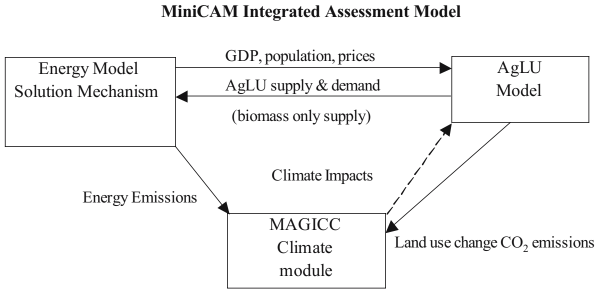



**Fig. 2** Data flow within the MiniCAM

## 2.2 Energy model

At the core of the MiniCAM Integrated Assessment Model is a partial-equilibrium economic model focused on energy consumption and greenhouse gas emissions. The energy model is an updated version of the Edmonds-Reilly-Barnes (ERB) energy model described in Edmonds and Reilly (1985) and described in more detail for a recent version in Brenkert et al. (2007). The energy model is designed to assess an array of present and potential future energy generation and transformation technologies. Included in the energy model are a large number of competing electric generation technologies such as: gas turbines, nuclear fission, commercial scale biomass, fusion, hydrogen fuel cells, fossil systems with geologic $CO_2$ sequestration, wind turbines and terrestrial solar PV. Potential end-use energy carriers include fossil fuels; electricity; synthetic liquids and gases; and hydrogen. Prior to this study, the energy model was coupled with the original version of the AgLU model, which lacked the land use allocation mechanism and several other enhancements present in the updated AgLU model.

## 2.3 MiniCAM integrated assessment model

To more fully examine the effects of $CO_2$ mitigation policies on global land use, the AgLU model was integrated into the MiniCAM by matching the energy model's demand for bioenergy crops with the AgLU model's bioenergy crop supply. This allows for an equilibrium price of bioenergy to be determined. Figure 2 is a schematic of the interactions within the MiniCAM. Climate change impacts on the agricultural sector are addressed elsewhere (Sands and Edmonds 2005).

The demand for bioenergy provided by the MiniCAM is derived from a comprehensive, long-term model of the energy system. Bioenergy can be used directly to produce heat as an end-use fuel or used to produce electricity, synthetic liquids and gases, or hydrogen for fuel cells.[3]

The supply of bioenergy crops is calculated by the AgLU model as the amount of land in bioenergy multiplied by the yield of bioenergy crops, both of which are determined by the land allocation mechanism. Figure 3 provides a sample global supply curve of biomass in 2050 as a function of bioenergy price, holding all else

[3] Hydrogen for fuel cells is only produced in scenarios that assume hydrogen fuel cell development as an energy end-use option.

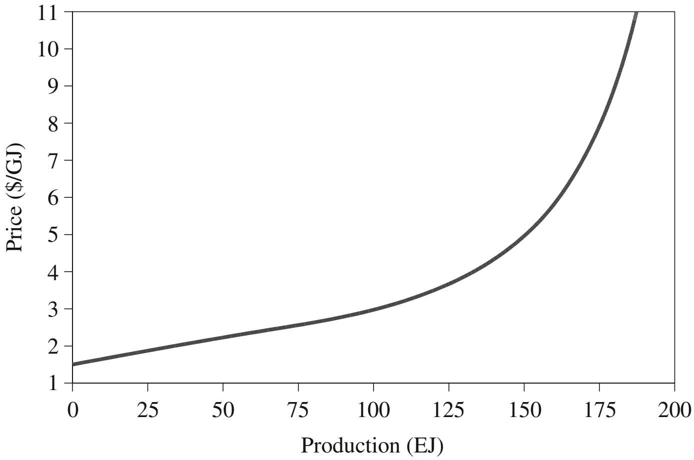



**Fig. 3** Example global supply of biomass as a function of biomass price. Biomass price is in dollars per gigajoule (GJ) and biomass supply is in exajoules (i.e., 10^18 J).For reference, 1 GJ=10^9 J=0.239 Gcal

constant. As the price rises to high levels, the marginal increase in bioenergy crop production slows, as most of the higher-yielding bioenergy cropland is under cultivation and it becomes more difficult to expand bioenergy crop production further. In this example bioenergy supply curve, if the price continues to rise to levels above 11 $/gigajoule (GJ), the production of bioenergy crops will eventually reach a threshold at approximately 250 exajoules (EJ) due to the finite global land base and the relatively inelastic demand for food crops. This is consistent with estimates of total potential bioenergy production found in Fischer and Schrattenholzer (2001).

## 3 Input data and assumptions

### 3.1 Baseline scenario data and assumptions

Looking ahead beyond the next decade or so, it becomes incredibly difficult to predict human social, economic and technological development in any deterministic sense. This analysis uses the most up-to-date scenarios available to examine several potential pathways. The scenarios examined here are the latest realizations of the scenarios developed by the Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC). The development of these scenarios is described in detail in the SRES report (Nakicenovic and Swart 2000) with the updated MiniCAM implementation discussed in Smith et al. (2005).

This study focuses on the SRES B2 scenario as the baseline case for analysis of the impact of bioenergy crops in a $CO_2$-constrained world. B2 was chosen for further analysis because it is a middle of the road scenario best described as “innovation as usual.” The other SRES scenarios represent other plausible assumptions. In the B2 scenario, global primary per capita energy use rises steadily from 72 GJ/capita in 1990 to 130 GJ/capita in 2095. The assumed population level begins to level off around 2095 at 9.5 billion people.

The technological change parameters used for fossil energy production in the B2 scenario used here are presented in Table 2. These parameters indicate the assumed improvement in the cost of fossil fuel extraction and are used in all time periods.

**Table 2** The assumed annual rate of technological improvement used in MiniCAM

| Resource | Annual rate of change (%) |
|---|---|
| Conventional oil | 0.75 |
| Conventional gas | 0.75 |
| Coal | 0.75 |
| Unconventional oil | 1.00 |
| Nuclear fuel | 0.5 |

These parameters are used in all time periods. The focus here is on bioenergy, and hence these parameters less relevant than the AgLU technological change parameters (Table 3), but are useful for comparison.

The technical change assumptions for agriculture (Table 3) represent possible future improvements in agricultural technology. The first 4 time periods, from 1990 to 2035, are assumed to follow the approximate historical rate of technological improvement in all crops from better crop management strategies, genetic engineering, and other agricultural practices (Pinstrup-Anderson et al. 1999). This is followed by a slow-down in technological improvement after 2035 as further improvements may become more difficult to achieve. There may be potential for greater gains in bioenergy crop productivity farther into the future, as is noted in Hansen (1991), but for the purposes of this study, bioenergy crops are assumed to follow the pattern of food crops. The values for technological change are key determinants of the model results, as discussed in the sensitivity analysis in Section 5.

## 3.2 Bioenergy data and assumptions

For this study, a single composite bioenergy crop is assumed to represent all potential bioenergy crops worldwide. To quantify this composite bioenergy crop, a conservative estimate of 9 dry metric tons per hectare per year (t $ha^{-1}$ $year^{-1}$) is used for the observed bioenergy yield in 1990 for model calibration, based on the studies in Table 4. Yields vary greatly due to different climates, soil conditions and agricultural practices, so we use a conservative estimate of yields for our reference case calculation (Hall and Scrase 1998).

Due to the fact that dedicated bioenergy crops are not currently in widespread production, there are no data to relate the bioenergy observed yield to the unobserved intrinsic yield, as required by the land allocation mechanism described above. Thus, it is assumed that the ratio of the intrinsic yield to the as-operated

**Table 3** The assumed annual rate of crop productivity improvement used in MiniCAM

| | First four time periods (%) | Second four time periods(%) |
|---|---|---|
| Forests | 0.5 | 0.5 |
| Food crops | 1.0 | 0.5 |
| Bioenergy crops | 1.0 | 0.5 |

**Table 4** A survey of bioenergy crop yield studies used to inform the choice of mean annual bioenergy crop yield in MiniCAM

| | Country | Crop | Mean annual yield (dry t/ha) |
|---|---|---|---|
| Graham et al. (1996) | USA | Willow (*Salix*) and poplar (*Populus*) | 5–17 |
| Graham et al. (1996) | USA | Switchgrass (*Panicum virgatum*) | 6–18 |
| Graham (1994) | USA | Short rotation woody crops (e.g., *Salix* and *Populus*) | 14 |
| Kheshgi et al. (2000) | USA | Short rotation woody crops (e.g., *Salix* and *Populus*) | 14 |
| Hanegraff et al. (1998) | Sweden and Netherlands | Willow and poplar | 7–9 |
| Azar and Larson (2000) | Tropics | Sugarcane | Maximum 20 |
| Carpentieri et al. (1993) | Tropics | Sugarcane | Maximum 20 |

yield is the same for bioenergy crops as for coarse grain crops. This ratio represents the average yield of a crop if it were planted on all available land as compared to the average yield if planted only where economically viable in competition with other crops. This ratio is less than one in all cases since crops tend to be most economically attractive if planted in locations where yield is high relative to other crops. In the United States this ratio is similar for different crops, which represents a combination of an efficient market system and a large productive land base. This assumption might not valid in other regions, or for other crops. Data, including simulation results, on the distribution of potential biomass crop yields relative to yields of other crops could be used to better define this parameter.

In contrast to the limited information on intrinsic yields, more data are available on the energy content value of bioenergy crops. Hall et al. (1993) use energy content values of 19.8 GJ dry $t^{-1}$ for hybrid poplar (*Populus*) and 17.5 GJ dry $t^{-1}$ for herbaceous crops, such as switchgrass (*Panicum virgatum*). Kheshgi et al. (2000) calculated an average energy content of 20 GJ dry $t^{-1}$ for hybrid poplar (*Populus*) and 17.6 GJ dry $t^{-1}$ for herbaceous crops. This study uses a conservative energy content estimate of 17.5 GJ dry $t^{-1}$ for the one aggregate biomass crop. This energy content estimate is used for conversion of bioenergy from units of dry tons to units of GJ in the calibration of bioenergy yields.

We also assume sustainable bioenergy crop cultivation practices. Lundborg (1998) analyzed the sustainability of bioenergy crops, and the results indicate that bioenergy is sustainable if there is a return of ashes or feedstock residue from the use of biomass to the soil from which the crops were harvested. Without return of residue, the soil would be depleted of essential nutrients and further production would require significant nutrient inputs and consequently higher greenhouse gas emissions. If sustainable bioenergy crop cultivation practices are not used in large-scale bioenergy production, then it may not be possible that bioenergy can be produced in the quantities indicated by the model results. At first, the lack of sustainable bioenergy crop cultivation practices will not have a substantial effect on bioenergy crop production. However, the depletion of essential nutrients would eventually serve to hinder bioenergy crop production in later time periods.

This study also does not examine waste or traditional biomass in detail. Waste and traditional biomass includes crop residues, animal waste, municipal waste, logging waste, food scrap and sawmill residues. Results from Fischer and Schrattenholzer (2001) indicate that waste biomass may have the potential to play a significant role in global energy production, but likely to a lesser degree than bioenergy crops. Waste biomass is included in the MiniCAM by employing a simple supply curve for waste and traditional bioenergy production. This supply curve is calibrated to the base year use and results in increases in waste biomass with biomass price increases.

### 3.3 Food crop and animal product elasticities

As this study will assess the potential influence of bioenergy crops on human food demand, current data on human per capita food demand must be analyzed to properly model human behavior with regard to food crop demand. Figure 4 illustrates the variation of per capita human food demand around the world (FAO 2001).

While per capita human food demand around the world varies greatly, due to income as well as cultural factors, a key observation is that the sum of calories from crops and processed crops remains within a certain range throughout all regions. This range extends from a low of just over 1,800 calories per person in Africa to a high of 2,500 calories per person in Korea. However, demand for animal products is much more variable between regions, and ranges from just over 100 calories per person in Africa to 900 calories per person in Australia and New Zealand.

So that simulated demand for food products falls within a reasonable range, the price elasticity for both food crops and processed crops are set to small and negative numbers, or zero, to indicate that the demand of food crops is highly inelastic but if it changes at all, it will decrease as the price of the crops rises. Similarly, the income elasticity of both food crops and processed crops are set to small and positive numbers. This indicates that people need a certain amount of basic food crops and even if their income rises, their food crop demand will increase, but not dramatically.

On the other hand, the historical data indicate that demand for animal products is more responsive to price and income. Hence, the price elasticities for animal products are set to be negative and greater in absolute value than the price elasticities of crops and processed crops. The price elasticity for beef, pork, and poultry products is set to −0.5.

The income elasticities for animal products are set to be positive and also greater in absolute value than those of crops and processed crops. These elasticity values are set so that food demands in developing countries approach the values seen in developed countries over the course of the century. In particular, the per-capita consumption of processed crops and meat products are assumed to increase as incomes in developing countries increase. Per-capita consumption of food grains is assumed to decrease slightly. The income elasticity of demand for beef, pork, and poultry products is set to according to region to either 0.1 or 0.2, with the exception of India, which is set to 0.3.

## 4 Results

### 4.1 $CO_2$ mitigation policies

We now examine bioenergy's role in the B2 scenario with several different $CO_2$ mitigation policies. To simulate possible $CO_2$ mitigation strategies, we constrain total fossil fuel $CO_2$ emissions along a pathway that leads to atmospheric $CO_2$ concentration

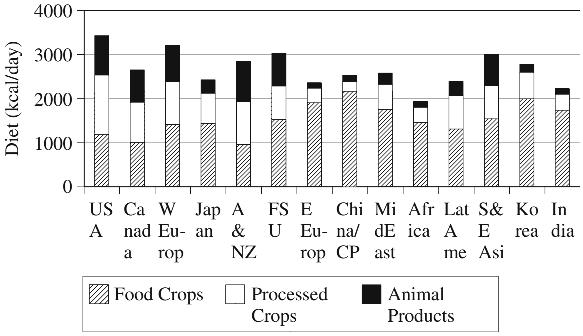



**Fig. 4** 1990 FAO data on food demand by region in kilocalories per day

levels of 650 parts per million by volume (ppmv), 550 ppmv, and 450 ppmv, following Wigley et al. (1996). The constraints are achieved through taxes on the carbon content of fuels that are adjusted to keep total fossil fuel emissions at a level at or below the specified pathway. Figure 5 illustrates the diverging emission paths for the different scenarios.

The taxes necessary to constrain the $CO_2$ concentration level for each pathway are illustrated in Fig. 6. A single global tax on the carbon content of fuel without regional differentiation is used in this study. That tax will be referred to as the *carbon price*, as it can represent the price in a tradable permits system or the level of the tax in a taxation system. For simplicity, advanced energy technologies such as geologic $CO_2$ sequestration and the presence of a hydrogen end-use infrastructure are not assumed to be available. The availability of these advanced energy technologies can drastically lower the carbon price needed to achieve a given emission target. The presence or absence of these technologies does not alter the fundamental conclusions of this study. However, availability of technologies such as geologic $CO_2$ sequestration could serve to reduce the demand for bioenergy, decreasing the expansion of bioenergy crops and the associated effects on land use, as described in the following sections.

The B2-450 scenario has a stringent $CO_2$ mitigation policy that substantially lowers fossil fuel emissions by 2095 relative to the baseline scenario. The impact of the 450 ppmv policy is especially noticeable in the later time steps of the model run, when the bulk of the reductions have to be made. To further illustrate this point, Fig. 7 displays the level of fossil fuel $CO_2$ emissions (in millions of metric tons of carbon per year) in each scenario.

The emission constraints used by MiniCAM apply only to fossil fuel emissions and not to land use change emissions. Land use change emissions contribute to the concentrations of $CO_2$ in the atmosphere, but these changes are not compensated for in these model experiments. Additional policies could be implemented to lower the impact of land use change emissions, but this study is focused on fossil fuel mitigation policies.

## 4.2 Impacts on the energy system

As the carbon price does not apply to sustainable bioenergy production, bioenergy becomes more competitive under the $CO_2$ mitigation scenarios. Figure 8 represents the influence that a 550 ppmv $CO_2$ policy has on the global energy mix. A clear result is that the share of the emission-free electricity sources, biomass and direct electric generation, increases significantly between the baseline case and the

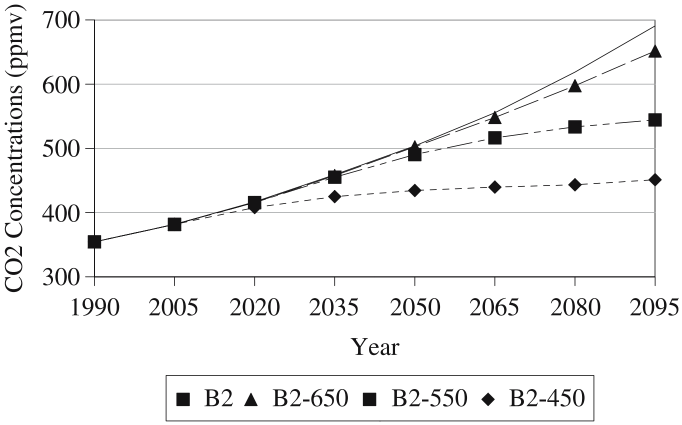



**Fig. 5** $CO_2$ concentration trajectories for baseline and carbon policy scenarios

550 ppmv policy case. Waste bioenergy expands first, followed by bioenergy crops. Direct electric generation includes all emission-free sources of energy such as wind, hydro, solar photovoltaic and nuclear power. Assumptions for global fossil resources are from Rogner (1997).

To more closely examine the impacts on the energy system of a $CO_2$ mitigation policy, the emission reduction is broken down into its component parts, following the Kaya Identity (Kaya 1989). The Kaya Identity states that total emissions are a function of gross domestic product (GDP), energy used per GDP output, and $CO_2$ emissions per energy used. Figure 9 uses this framework to illustrate that while the energy use per GDP decreases, the largest component of the emission reductions is a result of improvements in the amount of $CO_2$ emitted per energy consumed. These improvements represent the substitution of carbon-based fossil fuels, such as coal and oil, with carbon-free sources of energy, such as bioenergy. The energy use per GDP declined as well, representing a combination of end-use efficiency gains and service reductions. Very little of the reduction in emissions can be attributed to decreases in GDP, as GDP is only marginally affected by a 550 ppmv carbon policy in this model.

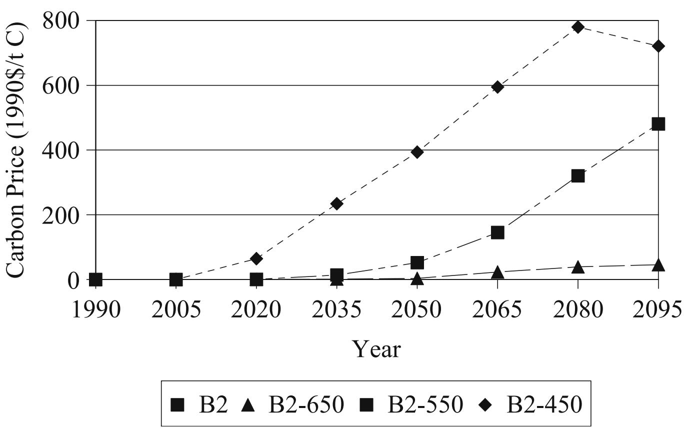



**Fig. 6** Global carbon price necessary to meet concentration targets in $1990 per ton of carbon

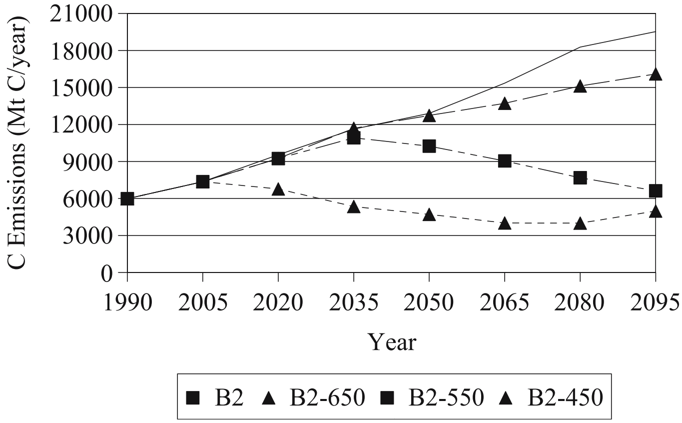



**Fig. 7** Fossil fuel carbon dioxide emissions in millions of metric tons of carbon per year

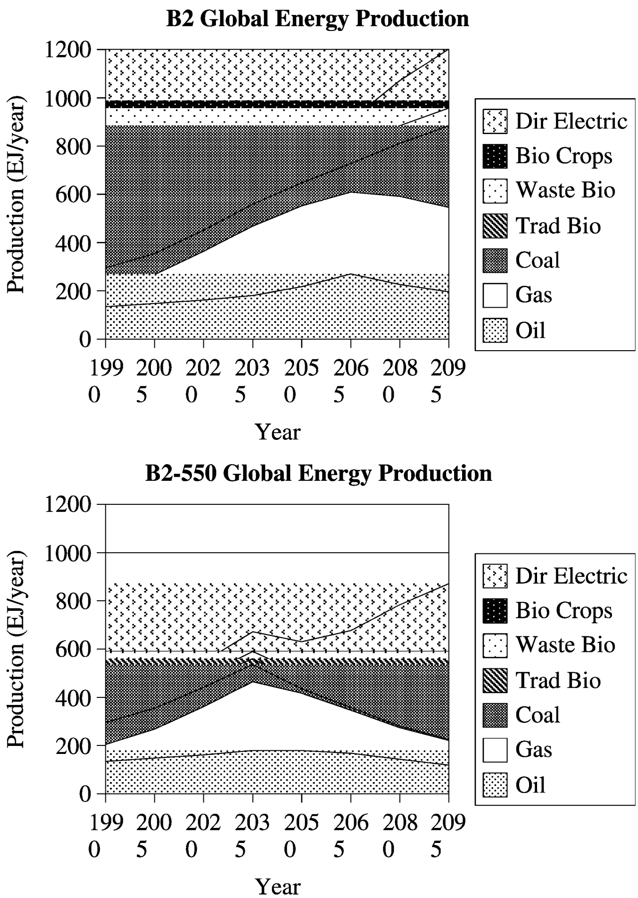



**Fig. 8** Global primary energy production. Direct electric includes all emission-free sources of electricity such as: wind, hydro, solar photovoltaic and nuclear power. Trad Bio is traditional bioenergy, Waste Bio is waste bioenergy, and Bio Crops is modern bioenergy crops

Figures 8 and 9 emphasize the importance of fuel switching in meeting a $CO_2$ concentration target. Figure 10 shows bioenergy crop production as a function of the $CO_2$ constraint. As the $CO_2$ target becomes more stringent over time, the production of bioenergy crops increases.

The estimates of potential bioenergy crop production compare favorably with the literature review of bioenergy potential estimates presented in Fischer and Schrattenholzer (2001) and Berndes et al. (2003). While there is no defined ceiling for bioenergy crop production in the model, the scarcity of productive land combined with competing food crop demands effectively caps the potential bioenergy crop production. As shown in Fig. 10, bioenergy crop production levels off around 200 EJ per year by 2100 under more stringent $CO_2$ mitigation policies, indicating an upper bound in the range of 200 EJ/year. The estimates of potential bioenergy crop production cited in Fischer and Schrattenholzer range from 140 EJ to 331 EJ by 2100, while the estimates in Berndes et al. extend this upper range to over 400 EJ by 2100. Most of these estimates in the literature are not directly comparable to the results of this study due to different sets of assumptions (e.g., carbon price); however, they indicate that the results of this study fall within the range in the literature.

### 4.3 Impacts on land use

Under all of the policies analyzed, the addition of a carbon price leads to an increase in fossil fuel prices and, in equilibrium, an increase in aggregate energy prices, including bioenergy prices. This increase in bioenergy prices has direct consequences on land use decisions, as growing bioenergy crops becomes more profitable relative to other land uses. Figure 11 provides insight into land use changes between the baseline and a 550 ppmv policy. It must be noted that this study does not account for potential forest carbon sequestration policies, so there is no incentive to grow or retain more forests under a $CO_2$ mitigation strategy in these scenarios.

As the bioenergy price increases, bioenergy crops successfully compete with other land uses, such as food crops, for some of the finite land supply. For instance, a farmer may find that he or she receives a greater rate of return by growing bioenergy crops and switches crops. This decision is based on the relative rate of return of each land use compared to other potential uses.

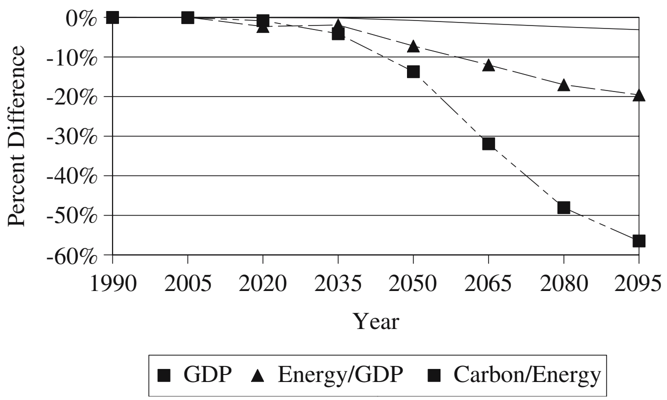



**Fig. 9** Source of emission reductions for the 550 ppmv carbon constrained case

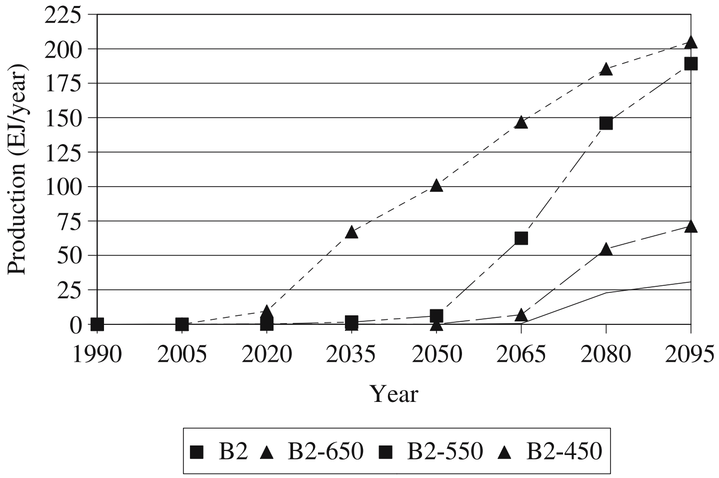



**Fig. 10** Global bioenergy crop production for the MiniCAM 2001 B2 base case and the three carbon-constrained scenarios (650, 550, and 450 ppmv stabilization cases)

The expansion of cropland tends to decrease the average yield of both food and bioenergy crops. Both types of crops will be grown first in the highest yield and most profitable land and gradually in lower yield, less profitable land if the price rises further. In this example, if more land is used for bioenergy cropland, the resulting competition for land increases land prices and, accordingly, crop prices. It then becomes profitable to convert more lower-yield land that is in other, less profitable land uses. This reduces the average yields. The same process also occurs, albeit to a lesser extent, for pasture and managed forest.

This behavior has a particularly significant impact on food crops. The more inelastic the demand for a good produced by a land use, the higher its relative price rises when compared to other potential land uses, given a decrease in supply. As discussed in Section 3, the demand for food crops is relatively inelastic compared to other products. Food production is therefore forced to expand more readily into more marginal lands than other land uses, such as forests or pastures. This results in a net *increase* in food cropland. Hence, the model results show that an important effect of a $CO_2$ mitigation policy is an increase in bioenergy and food cropland, and a decrease in pasture, managed forest and unmanaged land.

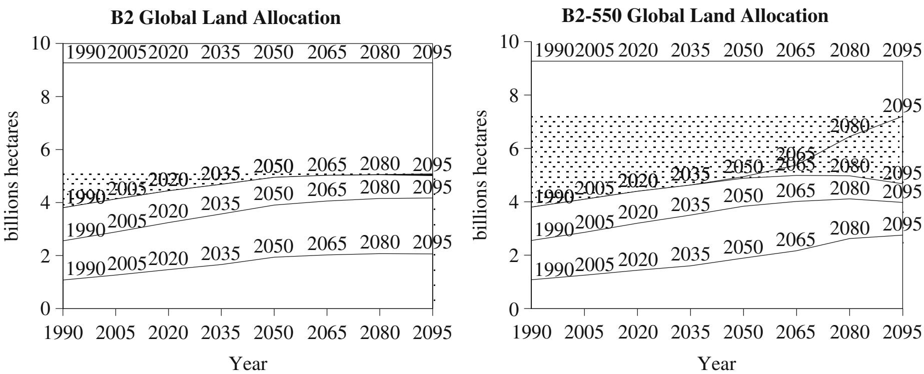



**Fig. 11** Global land allocation with and without a carbon policy

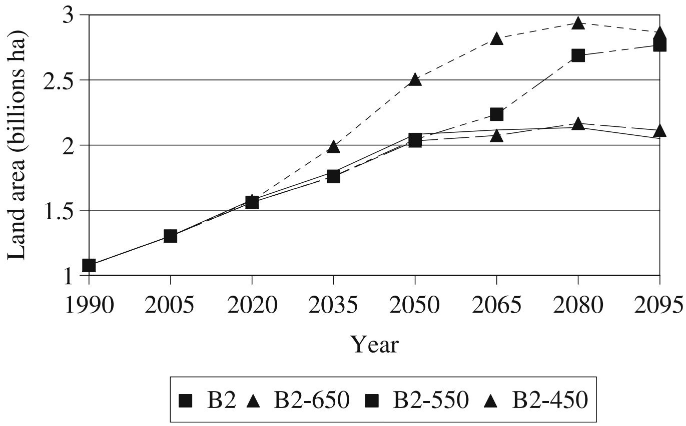



**Fig. 12** Global food cropland under different carbon constraints

To examine this phenomenon more closely, Fig. 12 presents global food cropland under the different $CO_2$ mitigation policies. The area used for production of food crops increases with the level of the $CO_2$ constraint.

The global increase in food cropland is mirrored by the increase in the relative price of food crops. The higher land rental rates from the introduction of profitable bioenergy results in rising food crop prices, as food crop demand is relatively inelastic. Figure 13 provides an example of the effect of $CO_2$ mitigation policies on the price of coarse grain food crops. Coarse grain food crops are the aggregate of the following staple crops: barley, maize, rye, oats, millet and sorghum.

The B2 reference case indicates slightly rising food prices due to increases in population and demand for food (for either direct consumption or use as feed) overwhelming the assumed crop productivity improvements. This implies the reversal of a trend of decreasing crop prices. While a long-term increase in crop prices is certainly possible, there is little evidence of this in the near term and the near-term increase shown in Figure 13 is likely due to limitations in the model structure as variable costs of production such as labor, fuel, and fertilizer for each crop are held fixed over time. A decrease in these costs over time would

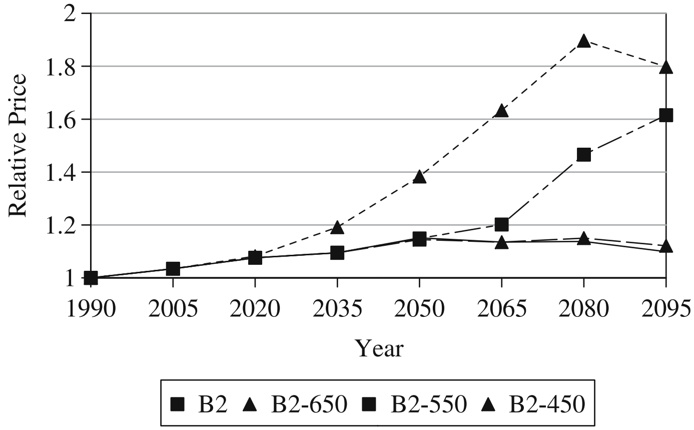



**Fig. 13** Global relative price of coarse grain crops

be more consistent with historical experience and would tend to decrease future prices, at least in the near-term. A change in this assumption will be examined in future work. Note, however, that the change in prices resulting from the more stringent climate policy scenarios is much larger than the baseline change. The relative increase in prices due to a climate policy is likely to be more robust than the small change in price in the baseline scenario.

In addition, alternative assumptions about the potential for greater utilization of agricultural land resources in many developing countries and the prospects for biotechnology would imply greater crop productivity improvements than in the B2 reference case. These alternative assumptions are examined in the sensitivity analysis, particularly focused on the effect of these assumptions on policy impacts.

Note that increases in food crop prices may have differing socio-economic impacts on different segments of the population. Farmers will likely benefit while urban populations would face higher prices.

The increase in global food cropland in the policy scenarios is further clarified by examining the effects of the increased demand for bioenergy crops on average yields. To be high-yielding, bioenergy crops compete most closely for the same quality of land as food crops.[4] Given that food crops have a fairly low price elasticity of demand, the increase in biomass demand in a policy scenario drives an increase in overall demand for food and bioenergy cropland. This increase in land comes at the expense of other, generally less productive, land uses. Lower-productivity land is thus added to bioenergy and food cropland, causing a decline in average yield.

When bioenergy is only grown in very limited areas, only the best land for bioenergy crops is used, and thus the yields are at their maximum, starting at 495 GJ $ha^{-1}$ $year^{-1}$. This starting value is high but possible, given the yields of up to 700 GJ $ha^{-1}$ $year^{-1}$ that have been reported in small-scale field trials (Berndes et al. 2001). As bioenergy crops expand, additional production, on average, shifts into increasingly less productive land. Thus, by 2095, average bioenergy crop yields drop to 328 GJ $ha^{-1}$ $year^{-1}$ in the B2-650 scenario, and just under 100 GJ $ha^{-1}$ $year^{-1}$ in the B2-550 and B2-450 scenarios. The drop in bioenergy yields mirrors the increase in bioenergy production. The low yield that is reached in the B2-450 scenario, 82.5 GJ $ha^{-1}$ $year^{-1}$, translates into a yield of 4.72 dry tons $ha^{-1}$ $year^{-1}$, which is near the very lower bound of economically feasible bioenergy yield estimates in the United States (Graham 1994). This indicates that by 2095, much of the bioenergy crop in the B2-450 scenario is being grown in less productive lands and limited additional opportunities for expansion exist.

In Fig. 14, food crop yields tell a similar story, although the scale of the effect is different. There is much smaller overall expansion since food crops already occupy a wider range of intrinsic land yields and have a much larger land base. This implies less expansion of food crops into less-productive lands. Thus, there is a much smaller decrease in food crop yields.

It is important to note that regional variation in food crop yields is very substantial in the base year and in the B2 scenario, crop yields are not assumed to converge. All regions experience a decrease in food crop yields in $CO_2$ mitigation scenarios when compared the base case, but the regional differences remain the same over time, due to the lack of convergence. Figure 15 provides a comparison of 2065

[4] Bioenergy crops may still be economical and used in more marginal lands, with correspondingly lower yields. An interesting extension of this research would be to examine policies to promote bioenergy crops only in wastelands or other more marginal lands so they do not compete directly with food crops.

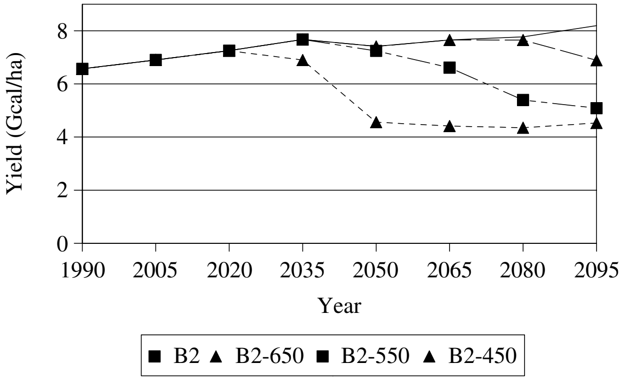



**Fig. 14** Global average food crop yield

average aggregate food crop yields by region to show both the wide variation of yield in a heterogeneous world and the effects of a $CO_2$ mitigation policy on regional food crop yields.[5]

Note the significant differences in average yield even among fully industrialized regions, both with and without the $CO_2$ mitigation strategy. The yield differences between developed countries can be attributed to a combination of differences in soil and climate conditions and differences in agricultural practices. Increased investment in the agricultural sector focusing in particular on developing nations (a "second green revolution") could decrease the gap between yields in the developing and developed countries. The general effect of such a change can be seen in the sensitivity analysis presented below — with increased yields anywhere in the world, given global markets, pressure on undeveloped land will decrease and less land will be required to meet food needs. Long-term analysis of the potential for agricultural improvements in different world regions is needed to develop consistent scenarios for future agricultural productivity increases.

### 4.4 Influence on food demand

Since a $CO_2$ mitigation policy leads to an increase in prices of both food crops, it also leads to a corresponding decrease in food demand. However, most of the decrease in food demand does not come from the inelastic food crops, but rather from the more elastic animal products. As the price of feed increases and the supply of pasture decreases from bioenergy expansion, the price of animal products increases and fewer animal products are consumed.

The decrease in per capita demand for animal products varies by region and by type of animal product, but all regions experience a drop in average per capita demand as bioenergy crops expand. Figure 16 presents the change in total per capita food demand in selected regions across the different scenarios. The United States

[5] The average food crop yield data on China is very likely biased upwards due to a systematic under-reporting of food cropland by China's State Land Administration. This is likely due to incentives created by agricultural policies in China. See Seto et al. (2000), Frolking et al. (1999), and Heilig (1999) for further details.

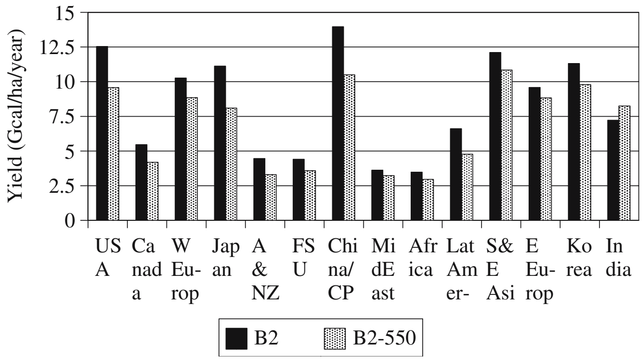
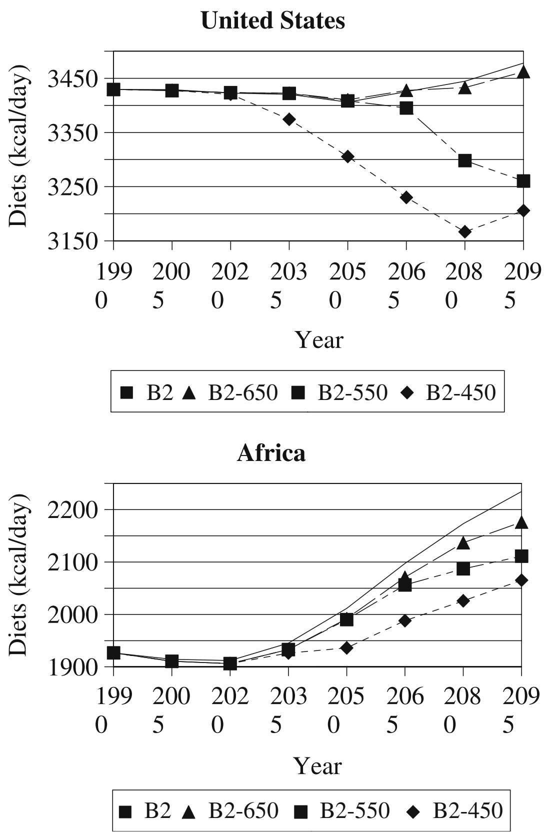



**Fig. 15** 2065 regional average food crop yields in base case and 550 ppmv constrained scenario

was chosen to represent food demand in the developed world, and Africa to represent food demand in the developing world.

The United States already has a high caloric diet with substantial animal product demand. In the baseline case, the United States shows very little change in food demand, as would be expected considering that most Americans are near a saturation

**Fig. 16** Per capita human food demand under different carbon policy scenarios. Note different scales



level for calories. However, in the mitigation policy cases, the price of animal products increases enough that the demand for animal products drops, leading to a decrease in total food demand. This result implies that for example, under a $CO_2$ mitigation policy, slightly less meat would be demanded in the United States (8% less by the end of the century in the most stringent case). It is possible that other policies would be implemented in the United States to prevent the price of food from rising and that would lessen the impact shown above.

Africa follows a different baseline case, but the relative effects of the $CO_2$ mitigation policies are similar. In the base year, Africa has very low levels of per capita food demand, at less than 1,950 kcals/day. Rao and Shastry (1986) estimate that a typical adult requires a minimum of 2,400 kcals/day for healthy active living, above the current level in Africa.

However, Africa has the potential to considerably increase its per capita food demand with the assumed increases in the rate of technological improvement of food crops and the exogenously assumed increases in income. Note that the B2 scenario assumes a heterogeneous world where income and food demand in developing nations does not converge with developed nations. In the SRES B2 scenario, Africa is assumed to increase its GDP from 0.379 trillion 1990 dollars in the 1990 base year to 24.5 trillion 1990 dollars by 2095 ($580 per capita in 1990 to $11,310 per capita in 2095, in 1990 dollars). Note that the B2 scenario was developed without consideration of AIDS in Africa, which could alter this trajectory.

The effect of a $CO_2$ mitigation policy on food demand in Africa has potentially important implications for poverty alleviation and starvation prevention. The results in Fig. 16 show that Africans are not quite as affected in absolute terms by the $CO_2$ mitigation policies as wealthier nations that eat more meat like the United States, but the impact on health and well being may be more significant. This may be particularly important for those living at the subsistence level in Africa. While all scenarios show increases in average food demand in Africa, the increases are substantially less in the more severe mitigation policies.

Note, however, that the $CO_2$ mitigation scenarios used here assumed the global adoption of a $CO_2$ mitigation policy. This may not be realistic in particularly low-income regions that lack fully functioning market mechanisms (or may not choose to participate). The effects of a policy on food demand should be considered illustrative, since the relationship between price, income, and demand are likely more complex than the simple representation used here. These results show that, if a global $CO_2$ mitigation policy promotes the large-scale production of bioenergy crops then the resulting competition for land will cause crop prices to increase, with potentially negative effects in low income regions. In this case, additional efforts would likely be needed in these regions to prevent negative impacts on food demand.

## 5 Sensitivity analysis

We now examine the sensitivity of our results to the parameters income growth, energy demand growth, population growth, and crop productivity improvements. We perform this sensitivity analysis with two objectives. First, we determine how sensitive the model reference case is to changes in each input parameter. In particular, we examine how proportional the changes in bioenergy production and food cropland are to changes in the input parameters. Second, we are interested in how these parameters affect the response to a $CO_2$ mitigation policy. To determine this, we examine the difference in cropland between the reference and policy cases under different assumptions.

### 5.1 Income growth

To determine the sensitivity of the MiniCAM results to the growth of income over time, we construct a sensitivity case with GDP 25% larger than the baseline B2 case by 2095. This sensitivity case has a global aggregate GDP of 263 trillion 1990 dollars, compared to 211 trillion 1990 dollars in the baseline B2 scenario. An increase in the growth of GDP primarily influences the model by increasing the demand for food products. To better isolate the effects of different parameters, total final energy demand is not changed and is examined separately from GDP growth.

We find that changing the assumed income growth does not greatly change the reference case behavior. The +25% GDP case has slightly lower bioenergy production than the B2 baseline case, with total bioenergy crop production in 2095 of 28.0 EJ/year as opposed to 30.7 EJ/year in the B2 case (Fig. 17). The +25% GDP case also has slightly more total food cropland than the B2 baseline. In 2095, there are 2.23 billion hectares of food cropland in the +25% GDP case and 2.08 ha in the B2 baseline case. These results imply an elasticity of bioenergy production with respect to GDP of−0.36 and an elasticity of food cropland with respect to GDP of 0.29.

To examine how different GDP assumptions change the effect of $CO_2$ mitigation policies, we construct a B2-550 policy case with GDP 25% larger than the baseline B2 case for all time periods. We then compare the difference between the B2 and B2-550 scenarios under the baseline GDP and the +25% GDP assumptions. Figure 18 shows how bioenergy production is affected by the GDP in the B2-550 scenario.

We find that there is little change in the difference between the B2 and B2-550 scenarios when GDP is increased by 25%. The largest change in how land use is affected is for food crops, which increases by 33.34% (from the reference to the policy case) under the baseline GDP scenario and increases by 29.79% in the +25% GDP scenario. This relatively small difference indicates that the assumption of different GDP growth rates has little effect on the policy results.

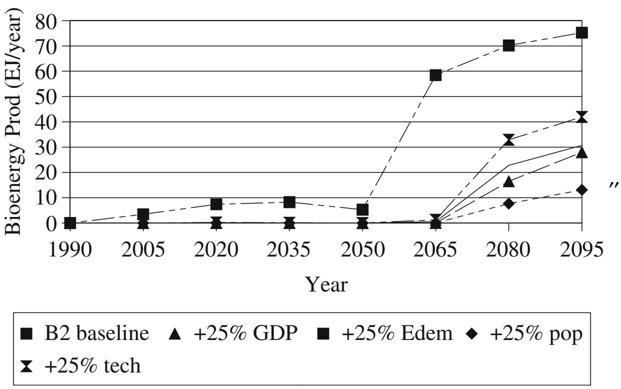



**Fig. 17** Bioenergy crop production in the B2 baseline and four sensitivity cases

## 5.2 Energy demand growth

The growth of final energy demand over time is a key assumption that plays an important role in the effect of $CO_2$ mitigation policies. To isolate the sensitivity of the model results to a change in the assumed growth of energy demand over time, we construct a sensitivity case with a final energy demand 25% greater than the baseline B2 case by 2095.

With a change in the assumed energy demand, the reference case behavior shows a considerable difference, particularly in bioenergy production, as evidenced in Fig. 18. The +25% energy demand case has a bioenergy crop production in 2095 that reaches 75.2 EJ/year, as opposed to 30.7 EJ/year in the B2 baseline case. The significantly greater bioenergy crop production is a result of the higher prices for energy stimulating the conversion of far more land to bioenergy cropland. The implied elasticity of bioenergy production with respect to energy demand is 5.8.

The demand for food does not change significantly under the +25% energy demand scenario, and thus total food cropland experiences only a minor change. Food cropland in 2095 uses 2.20 billion hectares in the +25% scenario and 2.08 billion hectares in the B2 baseline. This provides an implied elasticity of food cropland with respect to energy demand of 0.23, very close to the implied elasticity of food cropland with respect to GDP.

To determine the sensitivity of the model to the effect of a $CO_2$ mitigation policy under different energy demand assumptions, we compare the percent increase in land use between the B2 and B2-550 policies under the B2 baseline energy demand case and the +25% energy demand case. We find that the model results are not highly sensitive to the assumed growth in energy demand. As also found in the GDP sensitivity case, the greatest difference between the percent differences under the two energy demand paths in land use is for food crops. For food crops, the B2-550 policy leads to an increase in food cropland of 33.3% under the reference case, while under the +25% energy demand case the B2-550 policy leads to an increase of 27.1%. This lack of sensitivity indicates that the relative changes between B2 and B2-550 are not substantially affected by the assumed energy demand. Note that the final energy demand in the policy case is allowed to vary in response to the increase in energy prices due to the carbon price.

## 5.3 Population growth

To examine the sensitivity of the model results to population growth, the land use change with the B2 baseline population is compared to the land use change with the

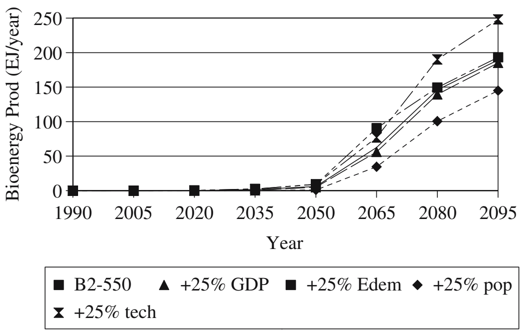
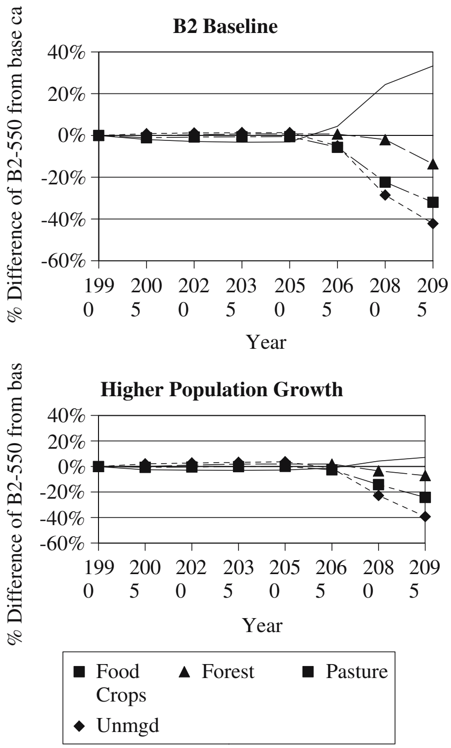



**Fig. 18** Bioenergy crop production in the B2-550 policy scenario and four sensitivity cases

**Fig. 19** *Top*, percent difference in land use between the B2 baseline and 550 ppmv carbon stabilization case. *Bottom*, same graph for a sensitivity case with a 25% increase in population for both baseline and policy cases




population increased by 25% by 2095. This results in a population of 11.9 billion people by 2095, rather than 9.5 billion in the baseline B2 scenario.

In the B2 reference case, both food cropland and bioenergy production are influenced by the assumed population growth. By 2095, the +25% population scenario has 3.89 billion hectares of food cropland versus only 2.08 billion hectares in the B2 baseline. The implied elasticity of food cropland with respect to population is 3.5. Similarly, bioenergy cropland in the reference case is sensitive to the assumed population. By 2095, the +25% population scenario has less than half the land in bioenergy production as the B2 baseline case: 0.034 billion hectares, compared to 0.070 billion hectares in the baseline. This implies an elasticity of bioenergy land with respect to population of −2.1.

This result occurs because the higher population growth increases demand for food cropland and pasture, raising the relative price of those land types when compared to bioenergy crops. Bioenergy cropland decreases; bioenergy prices are higher. Hence, bioenergy demand decreases and bioenergy production is lower.

The assumed population growth also has a noticeable effect on the influence of a $CO_2$ mitigation policy, a more considerable one in fact, than GDP growth or the growth in energy demand. Figure 19 shows the effect of higher population growth on the model results of the 550 ppmv $CO_2$ mitigation scenario.[6]

With food crops relatively more profitable under the higher population growth scenario, a $CO_2$ mitigation policy is less able to stimulate bioenergy crop growth, as

[6] Percent difference is calculated as follows: (policy land use-base land use)/(base land use).

is shown in Fig. 18. Thus, the effects of a $CO_2$ mitigation policy are damped, particularly for food crops.

### 5.4 Crop productivity improvements

To examine the sensitivity of the results to changes in the assumed crop productivity improvements, we construct a sensitivity case with the assumed crop productivity improvements for food crops and bioenergy crops increased by 25% for each time period (e.g., food crop productivity for the first four time periods grows by 1.25% each period, rather than 1% in the baseline).

With increased crop productivity improvements, less food cropland is required to feed the global population, allowing for more land to be allocated toward other uses. With +25% crop productivity, only 1.68 billion hectares are in food crop production by 2095, significantly less than the 2.08 billion hectares in the B2 reference case. At the same time, increasing bioenergy crop productivity allows bioenergy crops to be a more competitive fuel and when combined with less demand for food cropland, the result is an increase in bioenergy crop production (Fig. 20). In fact, there are 0.088 billion hectares of bioenergy cropland with +25% crop productivity and 0.070 billion hectares in the B2 base by 2095. These results imply an elasticity of bioenergy land and food cropland with respect to crop productivity of 1.02 and −0.77 respectively.

Figure 20 examines the percent difference between the baseline case and the 550 ppmv $CO_2$ mitigation policy for the assumed crop productivity improvement parameters in Table 3 and +25% increased technical change case. While the amount of land used for crops is decreased with increased productivity, the relative changes between B2 and B2-550 are not substantially affected by increased crop productivity. In both cases, bioenergy production increases: from 30 EJ/year to 178 EJ/year between B2 and B2-550 with the baseline productivity, and from 42 to 250 EJ/year in the +25% case. While the amount of land used for bioenergy crops under a climate policy is similar in both cases, improved biomass and crop productivity allows for a significantly larger production of bioenergy on the same amount of land. A similar pattern is seen for changes in food crop prices; crop prices increase between B2 and B2-550 significantly, but the relative changes between B2 and B2-550 are not substantially affected by increased crop productivity.

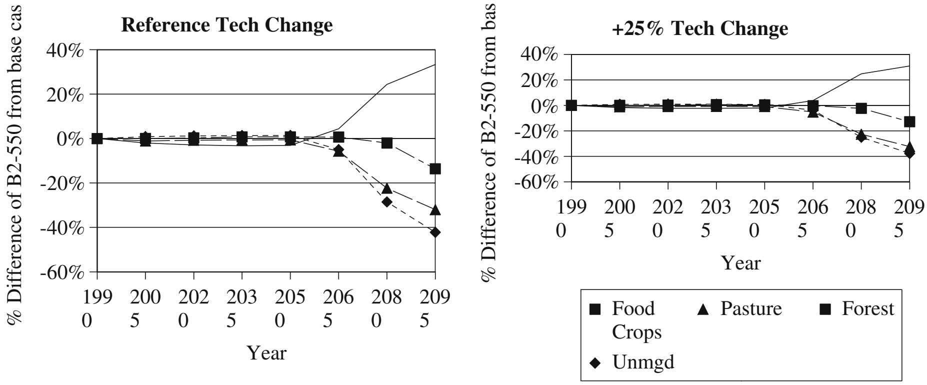



**Fig. 20** *Top*, percent difference in land use between the B2 baseline and 550 carbon stabilization case. *Bottom*, same graph with +25% crop productivity improvement parameters for both the baseline and policy cases

By increasing the rate of crop productivity improvements, both food crops and bioenergy crops require less land to meet their demand and thus the relative effects of a bioenergy policy tend to be damped. Under a $CO_2$ mitigation policy, there will be more bioenergy crop production with larger rates of crop productivity improvement (see Figs. 17 and 18).

Note that we assume bioenergy crops have the same rate of productivity improvement as food crops. However, it is possible that bioenergy crops have greater yield increase potential because less effort has been placed into plant breeding and cultivation technique development (Hansen 1991). The inverse could also be the case, particularly when the needs for inputs of water and fertilizer that could be required at higher yields are considered. As more research is done on this topic, the rate of crop productivity improvement for each crop should be reconsidered.

### 5.5 Synthesis

Food crop production is a key determinant of bioenergy crop production, as well as being important in its own right, and certain assumptions have a substantial impact on the food crop results. Food crop production is quite sensitive to the assumed population growth, with a 25% increase in population by 2095 increasing cultivated food cropland from 2.08 to 3.89 billion hectares in the reference case. It is also influenced by the assumed crop productivity improvements, but less affected by the assumed income growth and energy demand. The sensitivity to population assumptions implies that the results are also sensitive to the formulas used to estimate food demand.

Bioenergy crop production is most sensitive to the assumed energy demand, with a 25% increase in energy demand more than doubling the bioenergy crop production in the reference case. Bioenergy crop production is also considerably influenced by the assumed population growth and agricultural productivity improvements. Bioenergy crop production is not as sensitive to the assumed income growth.

The relative effects of a $CO_2$ mitigation policy are most sensitive to the population growth and agricultural productivity improvement assumptions. Increasing the assumed values of these parameters tends to dampen the effect of a $CO_2$ mitigation policy, particularly the effect of the policy on food crops. Given the potential for adoption of improved agricultural practices in the developing world, including developments in biotechnology, the crop productivity improvement assumptions are particularly uncertain. As noted above, larger yield increases imply that a $CO_2$ mitigation policy is less likely to reverse the century-long trends of decreasing food prices and increasing crop productivity. The relative effects of a $CO_2$ mitigation policy are less affected by the income growth and energy demand assumptions.

## 6 Conclusions

This study examines the interaction of the energy system and land use through the use of an integrated assessment model that combines energy supply, energy demand, and land uses including agriculture, forestry, and bioenergy crop production. The energy system is strongly linked to land use through the potential production of bioenergy crops that can be burned for heat, used for electricity production, or used as feedstocks to produce fuels such as ethanol or hydrogen. The use of agricultural and forestry residues for energy purposes also links these two systems, although this facet was not explored in detail here.

We have shown here that an aggregate, top–down representation of agricultural production and land use changes can produce realistic dynamics when linked with an energy-economic model. With the parameters used in this study, global biomass production from energy crops can reach 200 EJ, in line with results from other authors (e.g., see Fischer and Schrattenholzer 2001).

Biomass must compete with fossil and other non-fossil energy sources to supply energy services. The production of bioenergy crops, therefore, is sensitive to future total energy and food demands, particularly in a reference case without a climate policy (Fig. 17). In our reference scenario, bioenergy crop production is not widespread until the end of the century when increases in energy prices make their production profitable, although lowering the cost of producing bioenergy crops will shift the date at which bioenergy crops are produced closer to the present.

The situation is quite different in a policy case where emissions of $CO_2$ are limited and a premium is placed on carbon-free fuels such as biomass. $CO_2$ mitigation policies can raise the price of energy enough to stimulate a large production of bioenergy crops, up to 200 EJ/year by 2095 in a 450 ppmv $CO_2$ mitigation policy. Thus, bioenergy crops can provide a significant alternative to fossil fuels. The ultimate amount of bioenergy crops produced, however, is sensitive to the amount of land needed for food production and therefore is particularly sensitive to the assumed crop productivity improvements (Figs. 17 and 18). Several impacts on the agriculture and land use system result from an expansion of bioenergy crop production: decreases in forestland and unmanaged land, increases in the prices of food crops, and decreases in the yields of food crops due to competition with bioenergy crops for arable land.

Even under our reference case without an expansion of bioenergy these results imply a reversal of trends that have been in effect for the past few centuries, such as decreasing prices of food crops and increasing crop yields. Some portion of these changes in trends are likely due to limitations in the model structure as currently implemented. A combination of a more realistic assumption about decreases in variable costs and changing accessibility of potential farmland in South America and Africa would likely alter this result, particularly for the near term. A robust result of our analysis is that the expansion of bioenergy production will result in an increase in crop prices as bioenergy crops compete for land with food crops. Sensitivity analysis indicates that the effect of a $CO_2$ mitigation policy on food crop production may be considerably dampened with larger assumed crop productivity improvements. Nevertheless, these effects of the $CO_2$ mitigation policies should be kept in mind by policy-makers, while recognizing the uncertainty in the baseline assumptions.

Similarly, policy-makers designing $CO_2$ mitigation policies should recognize interactions with other land-use policies that may act as an impediment to the diversion of land to bioenergy production. For example, the expansion of bioenergy crops could decrease biodiversity – a case where one environmental policy may impact the effectiveness of another.

The work presented here is an initial step in the analysis of the coupled land use and energy systems. This study has not addressed other potential effects of $CO_2$ mitigation policies on the land use and agricultural system, such as the possibility of increased land use change $CO_2$ emissions due to decreases in unmanaged and forestland (Sands and

Leimbach 2003). In addition, water constraints and other inputs to agricultural production are implicitly modeled in the land allocation mechanism, but as they are key factors in future agricultural productivity, and further work will be needed to identify the roles these constraints might play in determining future land allocation. Similarly, additional research is warranted in examining how $CO_2$ mitigation policies might be coupled with, or influence, technology transfer in the agricultural sector.

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## References

Azar C, Larson E (2000) Bioenergy and land-use competition in Northeast Brazil. Energy Sustainable Develop 4(3):51–58

Berndes G, Azar C, Tomas K et al (2001) The feasibility of large-scale lignocellulose-based bioenergy production. Biomass Bioenergy 20:371–383

Berndes G, Hoogwijk M, van den Broek R (2003) The contribution of biomass in the future global energy supply: a review of 17 studies. Biomass Bioenergy 25:1–28

Brenkert A, Smith S, Pitcher H et al (2007) MiniCAM Documentation. available upon request

Carpentieri C, Larson E, Woods J (1993) Future biomass-based electricity supply in Northeast Brazil. Biomass Bioenergy 4(3):149–173

Edmonds J, Reilly J (1985) Global energy: assessing the future. New York, Oxford University Press

Edmonds J, Wise M, Sands R et al (1996) Agriculture, land use, and commercial biomass energy, Pacific Northwest National Laboratory Report SA-27726, Richland, WA

Edmonds J, Wise M, Pitcher H et al (1997) An integrated assessment of climate change and the accelerated introduction of advanced energy technologies: an application of MiniCAM 1.0. Mitig Adapt Strategies Glob Chang 1:311–339

Fischer G, Schrattenholzer L (2001) Global bioenergy potentials through 2050. Biomass Bioenergy 20 (3):151–159

Food and Agriculture Organization of the United Nations: 2001, *FAOSTAT data base*, http://apps.fao.org

Frolking S, Xiao X, Zhuang Y et al (1999) Agricultural land-use in China: a comparison of area estimates from ground-based census and satellite-borne remote sensing. Glob Ecol Biogeogr 8(5):407–416

Graham R (1994) An analysis of the potential land base for energy crops in the conterminous United States. Biomass Bioenergy 6:175–189

Graham R, Allison L, Becker D (1996) ORECCL-Oak Ridge Energy Crop County Level Database. *Proceedings of BIOENERGY '96—The Seventh National Bioenergy Conference: Partnerships to Develop and Apply Biomass Technologies*, Nashville, TN

Hall D, Scrase J (1998) Will biomass energy be the environmentally friendly fuel of the future? Biomass Bioenergy 15(4–5):357–367

Hall D, Rosillo-Calle F, Williams R et al (1993) Biomass for energy: Supply prospects. In: Johansson TBJ, Kelly H, Reddy AKN, Williams R (Eds) Renewable energy: sources for fuel and electricity, Washington, DC, Island Press

Hanegraaff M, Biewinga E, Van der Bijl G (1998) Assessing the ecological and economic sustainability of energy crops. Biomass Bioenergy 15(4–5):345–355

Hansen E (1991) Poplar woody biomass yields: a look into the future. Biomass Bioenergy 1:1–7

Heilig G (1999) ChinaFood. Can China feed itself?, CD-ROM Vers. 1.1. Laxenburg, Austria, International Institute for Applied Systems Analysis

Kaya Y (1989) Impact of Carbon Dioxide Emissions on GNP growth: Interpretation of Proposed Scenarios, Geneva, Switzerland, IPCC/Response Strategies Working Group, Intergovernmental Panel on Climate Change

Kheshgi H, Prince R, Marland G (2000) The potential of biomass fuels in the context of global climate change: Focus on transportation fuels. Ann Rev Energy Environ 25:199–244

Lundborg A (1998) A sustainable forest fuel system in Sweden. Biomass Bioenergy 15(4–5):399–406

Nakicenovic N, Swart R (eds.) (2000) Special report on emissions scenarios. Cambridge, United Kingdom, Cambridge University Press

Pinstrup-Anderson P, Pandhya-Lorch R, Rosengrant M (1999) World food prospects: critical issues for the early 21st Century. Washington, DC, International Food Policy Research Institute

Raneses A, Hanson K, Shapouri H (1998) Economic impacts from shifting cropland use from food to fuel. Biomass Bioenergy 15(6):417–422

Rao P, Shastry G (1986) Changes in diet and nutrition profile in ten states in India, Hyderabad, India, Nutrition News, National Institute of Nutrition, 7(2)

Rogner H (1997) An assessment of world hydrocarbon resources. Ann Rev Energy Environ 22:217–262

Sands R, Edmonds J (2005) Climate change impacts for the conterminous USA: an integrated assessment, paper 7: economic analysis of field crops and land use with climate change. Clim Change 69(1):127–150

Sands R, Leimbach M (2003) Modeling agriculture and land use in an integrated assessment framework. Clim Change 56(1):185–210

Seto K, Kaufmann R, Woodcock C (2000) Landsat reveals China's farmland reserves, but they're vanishing fast. Nature 406(6792):121

Smith S, Pitcher H, Wigley T (2005) Future sulfur dioxide emissions. Clim Change 73(3):267–318

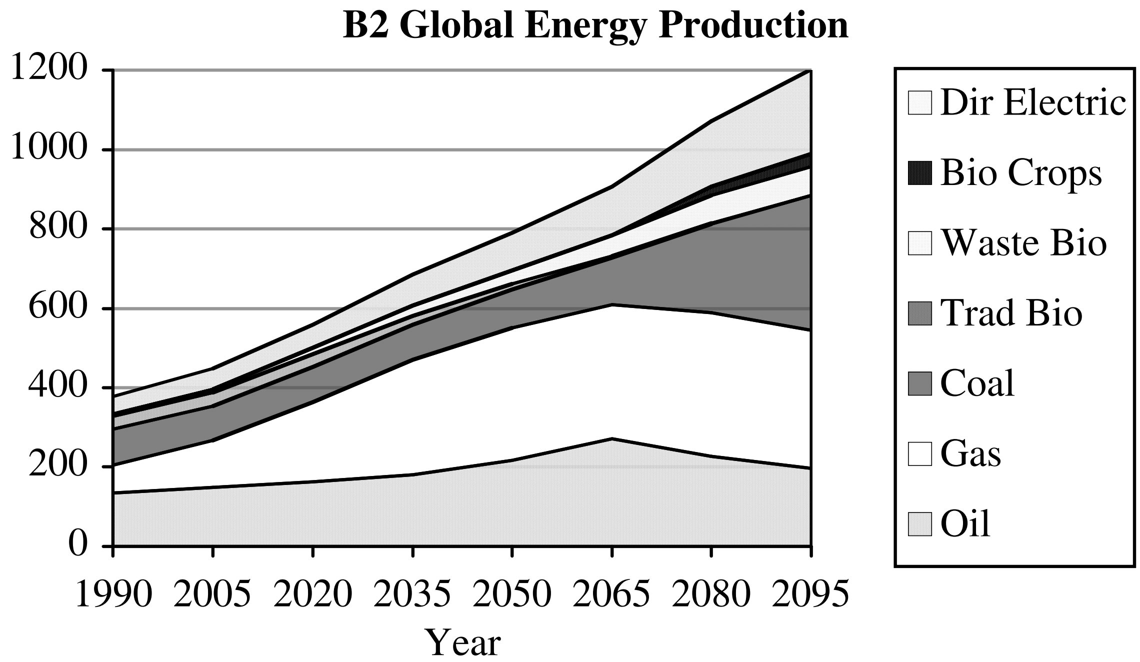
Wigley T, Richels R, Edmonds J (1996) Economic and environmental choices in the stabilization of atmospheric CO2 concentrations. Nature 379(6562):240–243

Yamamoto H, Yamaji K, Fujino J (1999) Evaluation of bioenergy resources with a global land use and energy model formulated with SD technique. Biomass Bioenergy 63(2):101–113

Yamamoto H, Yamaji K, Fujino J (2000) Scenario analysis of bioenergy resources and $CO_2$ emissions with a global land use and energy model. Biomass Bioenergy 66(4):325–337

Yamamoto H, Yamaji K, Fujino J (2001) Evaluation of bioenergy potential with a multi-regional global-land-use-and-energy-model. Biomass Bioenergy 21(3):185–203

**ERRATA**



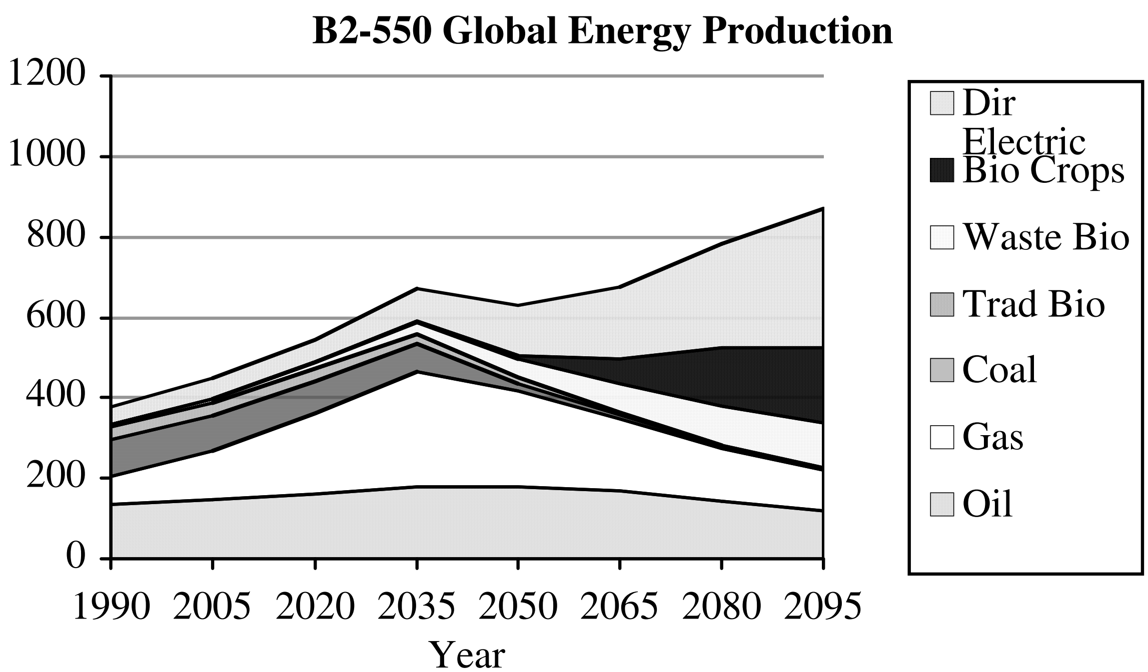




Figure 8. Global primary energy production. Direct electric includes all emission-free sources of electricity such as: wind, hydro, solar photovoltaic and nuclear power. Trad Bio is traditional bioenergy, Waste Bio is waste bioenergy, and Bio Crops is modern bioenergy crops.

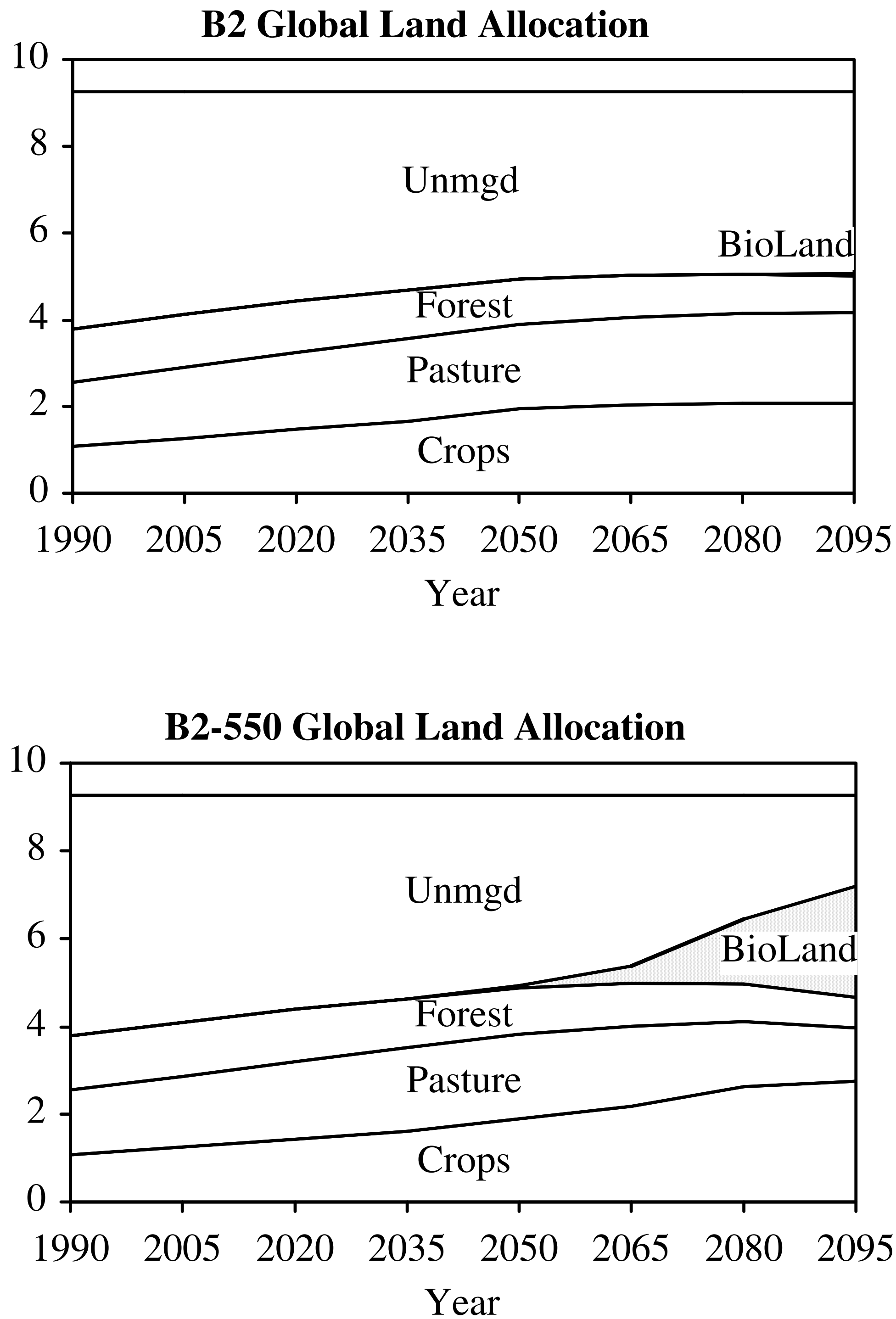



Figure 11. Global land allocation with and without a carbon policy.

[Please place side-by side if practical.]