Assessing the Interactions among U.S. Climate Policy, Biomass Energy, and Agricultural Trade

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ABSTRACT

Energy from biomass is potentially an important contributor to U.S. climate change mitigation efforts. However, large-scale implementation of bioenergy competes with other uses of land, including agriculture and forest production and terrestrial carbon storage in non-commercial lands. And with trade, bioenergy could mean greater reliance on imported energy. Based on EMF-24 policy specifications, this paper explores these dimensions of bioenergy's role in U.S. climate policy and the relationship to alternative measures for ameliorating the trade and land use consequences. It shows how widespread use of biomass in the U.S. could lead to imports; and it highlights that the relative stringency of domestic and international carbon mitigation policy will heavily influence the amount of imports. It demonstrates that limiting biomass imports could alter the balance of trade in other agricultural products. Finally, it shows that increasing efforts to protect both U.S. and international forests could also affect the balance of trade in other agricultural products.

Keywords: Biomass, Bioenergy, Land use, Climate mitigation, Agricultural trade

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1. INTRODUCTION

Energy from biomass (bioenergy) is potentially an important contributor to U.S. climate change mitigation efforts. Substituting biomass for fossil fuels in the energy system for uses such as generating electricity or creating liquid fuels could reduce CO_2 emissions. However, there are issues associated with large-scale reliance on bioenergy. One of the major issues is that biomass production competes with other uses of land, notably crop production and production of forest products. Because land is limited, expansion of land dedicated to biomass production would cause increased competition for land, potentially reducing the amount of land used for these other productive uses. In addition, expansion of cropland to produce biomass could reduce land in forest in general, both commercial and noncommercial, increasing land use change emissions as lands such as high-carbon forest is converted to lower-carbon cropland or land for biomass production. This issue of indirect land use emissions from biomass has been identified and studied by several authors, notably Fargione et al. (2008), Searchinger et al. (2008), Wise et al. (2009), and Havlik et al. (2011). The potential for policies that prohibit the expansion of cropland for biomass into forested lands and other non-commercial land types has been quantified by Melillo et al. (2009) and Popp et al.

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(2012). A comprehensive review of issues related to biomass production, technologies, use and its potential impacts on land use, greenhouse gas emissions, food production, and other issues of sustainability is provided by Chum et al. (2011).

An issue that has not been as widely studied is that a reliance on biomass could influence the balance of trade, foremost in biomass itself, but also potentially in other agricultural products. Domestic-focused studies of biomass production potential often assume, either explicitly or implicitly, that biomass production would not be done in a manner that affects food production and the U.S. position of being a major exporter of products (see, for example, DOE 2011). However, agricultural products are heavily traded internationally, and a large-scale commitment to domestic production of biomass at levels of demand associated with deep carbon emissions reduction could affect the U.S. agricultural trade position in biomass and food crops. On the other hand, the U.S. could also end up being a large-scale importer of biomass under an aggressive climate mitigation policy assuming its import is allowed.

Partly in response to these issues, the standard assumption to be used for the EMF-24 scenarios was that the U.S. could only use domestically-supplied biomass (see Fawcett et al., this volume). In this paper, we explore the implications of that assumption, as well as the impact of restrictions on land use change. For this study, we interpret the EMF-24 assumption as an explicit approach to limit the trade in biomass, ensuring that U.S. climate policy does not depend on biomass energy imports. To address the issue of emissions from land use change, we explore scenarios in which protections on forests are implemented to ensure that increased biomass production does not result in decreased forest land and associated land use change emissions.

This paper uses the EMF-24 scenarios as a starting point to explore the relationship between U.S. climate policy and trade in biomass and agriculture products. In particular, it focuses on four related questions. (1) How might U.S. climate policy influence trade in biomass? (2) How might U.S. climate policy influence trade in other agricultural goods? (3) How might efforts to reduce biomass imports influence trade in other agricultural products? (4) How might efforts to protect forests influence trade in other agricultural products? The GCAM integrated assessment model is used throughout the paper as the means to explore these questions.

We proceed to address these questions in two steps. In the first step, we focus on the impacts of the U.S. domestic climate policy on trade balances of biomass and other crops based entirely on the EMF-24 scenarios, but assuming no limits on biomass trade or on change in forested land. The wide-ranging technology scenarios of EMF-24 along with the various levels of U.S. climate policy in the EMF-24 scenario design provide an ideal vehicle to illustrate the mechanisms through which U.S. domestic climate policy might influence biomass and agricultural trade balances, and reveal the conditions that either increase or decrease such effects.

In the second step, we explore two policies, independently and together, intended to ameliorate some of the negative impacts of bioenergy. First, we model a biomass trade restriction policy where the U.S. can neither import nor export biomass. Second, we model a forest protection policy to represent a plausible reaction to biomass expansion into forest and land use change emissions, similar in a broad sense to a REDD policy (United Nations, 2008) though here applied as a strict global constraint. Both of these policies will have intended consequences, but it is important to also understand the potential unintended consequences they might have on trade in other agricultural products.

The remainder of the paper proceeds as follows. In Section 2, we briefly introduce the GCAM and provide links to additional documentation of its land use model component in particular. In Section 3 we provide the details of the design for the study. Section 4 and Section 5 provide the results of the analysis, first focusing on scenarios without trade or forest restrictions (Section 4) and then adding those in (Section 5). We close in Section 6 with final thoughts on the importance of understanding the interconnected nature of energy, land, and global market when designing U.S. climate policy.

2. GLOBAL CHANGE ASSESSMENT MODEL

The model we used to project each scenario into the future is the Global Change Assessment Model (GCAM). GCAM[1] (Clarke et al., 2007, Edmonds and Reilly, 1985) is an integrated assessment model that links a global energy-economy-agricultural-land-use model with a climate model of intermediate complexity. As part of GCAM's modeling of human activities and physical systems, GCAM tracks emissions and concentrations of the important greenhouse gases and short-lived species (including CO_2, CH_4, N_2O, NO_x, VOCs, CO, SO_2, BC, OC, HFCs, PFCs, and SF_6). GCAM is a market equilibrium model. It operates by solving for the set of prices in global and regional markets such that supplies and demands are in balance. At this model solution, all markets are in equilibrium. The version of GCAM used for this analysis was GCAM 3.0.[2,3]

GCAM subdivides the world into fourteen regions and operates from 2005 to 2095 in five-year increments. The agriculture and terrestrial system (Wise et al. 2011) further subdivides each of the GCAM's fourteen geopolitical regions into as many as eighteen sub-regions, based on the agro-ecological zones described by Monfreda et al. (2009). GCAM computes the supply and demand for primary energy forms (e.g., coal, natural gas, crude oil), secondary energy products (e.g., electricity, hydrogen, refined liquids), several agricultural products (e.g., corn, wheat, rice, beef, poultry, etc.). GCAM typically assumes global trade in fossil fuels and agricultural products, but can be operated with markets defined regionally. GCAM models three sources of lignocellulosic biomass supply: purpose grown crops that require dedicated land such as switchgrass and woody crops, residues from agriculture and forestry operations, and organic municipal solid-waste (Luckow et al. 2010). When we refer to *biomass* in this paper, we are referring to these lignocellulosic resources rather than energy derived from first generation resources such as starches and oil crops, although they are included in GCAM.

GCAM models several pathways for using lignocellulosic biomass in the energy system including production of electricity, liquid fuel, gas, and hydrogen. Biomass can also be consumed directly to provide end use heat. In the climate mitigation policies studied here, the use of biomass with carbon dioxide capture and storage (CCS) becomes an important source of electricity and liquid fuels in technology scenarios where CCS is available. GCAM includes the energy and cost required to collect, process by pelletizing or briquetting, and transport biomass for use in the energy system, with an approach and data from a study by Hamelinck et al. (2005). Luckow et al. (2010) describes in detail the data sources and values used in GCAM for biomass technology costs and energy conversion efficiencies. In addition, the greenhouse gas emissions that result from growing biomass and other crops, including those from fertilizer use, are also modeled in GCAM, with methods and data detailed by Kyle et al. (2011). With the noted exception of CO_2 emissions from

1. Note that GCAM was formerly known as MiniCAM.

2. It is not possible in this paper to fully document the GCAM model, so readers are encouraged to explore the GCAM documentation, and particularly the extensive documentation on the modeling of agriculture and land use, found at found at wiki.umd.edu/gcam.

3. For simplicity, we will refer to GCAM 3.0 simply as GCAM for the remainder of this paper.

Table 1: Scenario components

Baseline	
LowTech	all low tech (US23F)
BioRE	advanced bioenergy and renewables (US01F variant)
NucCCS	advanced nuclear and CCS (US21F)
Adv	all advanced supply tech (US15F)
AdvEE	all advanced supply tech and high end-use efficiency (US13F)
Emission constraints (indexed to 2005)	
Unconstrained (baseline)	
USA 50% abatement by 2050	
USA 80% abatement by 2050	
Other Constraints	
Trade	free trade of biomass, no constraints
Restrict	trade restriction on biomass
USA Protect	USA protected forest (non-commercial)
Global Protect	Global protected forest (non-commercial)

land use change, greenhouse gas emissions from growing and using biomass are included in the policy caps for the EMF-24 study (Fawcett et al., this volume).

All of the GCAM scenarios modeled in this paper share the same economic, demographic, natural resource and other critical assumptions described by Thomson et al. (2011)[4]. In particular, all scenarios assume a global population that grows until mid-century, peaks in 2065, and declines to approximately 9 billion between 2065 and 2100. Living standards continue to increase and technological improvements in the production of energy, energy-related services, and agricultural goods continue to occur throughout the century.

3. STUDY DESIGN

This study is based on the domestic policy and technology scenarios developed for EMF-24[5]. All of the scenarios explored in the study are summarized in Table 1.

3.1. Scenarios exploring the effect of technology and mitigation level

In the first portion of the analysis, we explore five of the core scenarios from the EMF-24 scenario set, which cover a wide range of future technology development pathways, as defined in Fawcett et al. (this volume). They include the extremes from the EMF-24 scenario set – the low technology development scenario (LowTech) and advanced technology development scenario (Adv) – along with the BioRE and NucCCS cases. In addition, we include a technology scenario that features advanced technology along with high end-use efficiency assumptions to represent the most

4. Note these are GCAM assumptions and not standardized to all models in EMF-24.
5. For more information on the EMF-24 scenario design, see Fawcett et al., this volume.

optimistic future in terms of energy technology development. The benefit of this spread of technology assumptions is that it captures a wide range of potential roles and deployment scales for bioenergy.

Along with these five technology sets, we overlay three different levels of domestic emission abatement policy, consistent with the EMF-24 design: unconstrained baseline, 50% abatement of greenhouse gas emissions (GHGs), not including CO_2 emissions from land use change, by 2050 and 80% abatement of GHGs, not including CO_2 emissions from land use change, by 2050. Again, consistent with the EMF-24 design, the rest of the world (RoW) is assumed to follow "muddling through" pathway, in which the more developed countries reduce emissions by 50% by 2050, less ambitious actions take place in some other countries, and no reductions in some fossil exporting countries. Note that this international policy regime holds irrespective of the U.S. policy regime. Note also that the international policy regime does not include the type of policy on carbon in land that was described in Wise et al. (2009); that is, there is no incentive in terms of an economic value placed on terrestrial carbon either to halt deforestation or encourage afforestation internationally.

3.2. Scenarios exploring the implications of restrictions on biomass trade and forest protection

In the second portion of the analysis, and to explore the implications of biomass trade and forest protection, we then select one focus case with advanced energy supply technologies (Adv) and stringent climate policy of 80% abatement by 2050. We then overlay different two biomass trade regimes and several degrees of forest protection.

Two trade regimes are considered to observe the effect of trade restrictions on biomass. The baseline "Trade" regime assumes free trade of biomass without any constraints. The alternative "Restrict" regime assumes no trade in biomass; that is, all domestic use of biomass must be supplied by domestic production.

Three levels of forest protection policies, including no protection, are considered. The baseline case assumes no particular forest protection policy is enforced, and biomass land and cropland are free to expand into the forest. The two protection cases assume that all non-commercial forest are protected and conversion to other land uses is not permitted. In the first of these, we assume only that U.S. forests are protected, while in the second, we assume global forest protection.

4. RESULTS: EFFECTS OF TECHNOLOGY AND POLICY STRINGENCY

4.1. Biomass in the context of the full energy system

Before discussing specific biomass and trade results, it is useful to see biomass use in these scenarios in the context of the entire energy system.[6] Figure 1 shows GCAM results for U.S. primary energy use in 2050 in each of the technology and mitigation scenarios. Biomass is a significant mitigation option across all of the technology scenarios, and it is especially important when there are few other options available (Low Tech and BioRE). When all mitigation options are constrained in the LowTech scenario, there is a large reduction in total energy use. In contrast when all major abatement technologies are present, the reduction in overall energy consumption is substantially smaller.

6. See Clarke et al. (this volume) for an overview of results from GCAM and the other participating models.

Figure 1: Year 2050 U.S. Primary Energy Consumption by technology and policy scenario (measured in electricity generated for nuclear, and non-biomass renewable)

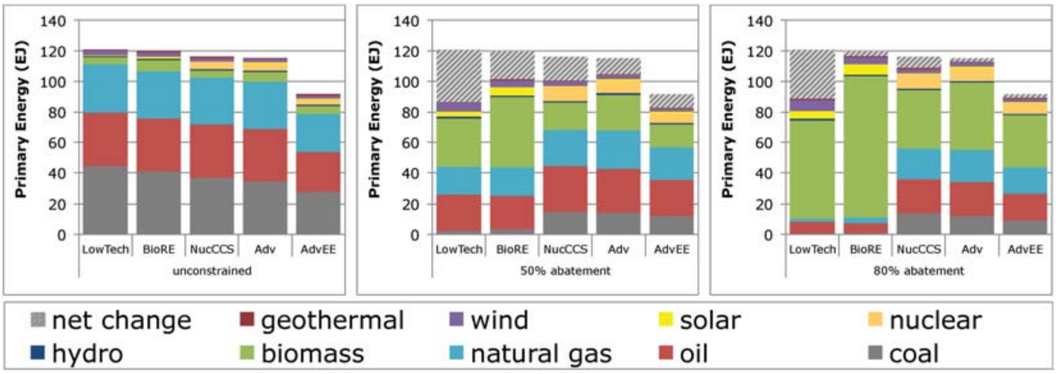
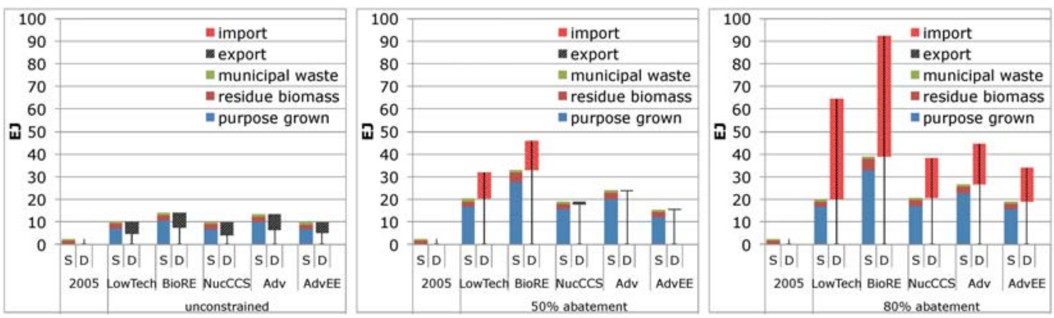


Figure 2: 2050 biomass production and trade by scenario. Emphasis on U.S. domestic climate policy and future technology development pathways. S, supply; D, demand.

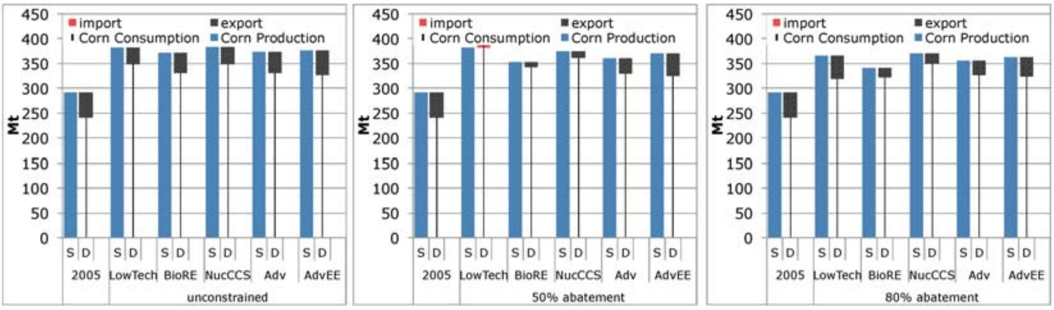


When advanced nuclear and CCS are available (NucCCS, Adv, and AdvEE), biomass use is moderate for the 50% abatement level, with nuclear and fossil fuel with CCS options playing a large role. However, at stringent abatement level (80%), all abatement technologies are fully utilized, including large increase in bioenergy use. In scenarios where CCS is available, most of the use of coal, gas, and biomass is done with CCS by 2050. When CCS is not available, the 80% abatement level leaves much less room for fossil fuel use.

4.2. Biomass production and trade

Figure 2 surveys the effects of policy and technology on the trade of biomass specifically. Across all technology assumptions, the U.S. becomes a net exporter of biomass by 2050 when there is no U.S. climate policy (the left panel in Figure 2). Because some other countries are taking on 50% reductions in greenhouse gas emissions as part of the international assumptions for EMF-24, these countries demand bioenergy as part of their low-emissions portfolio. Just as any other crop, the biomass is supplied from the agricultural regions where the relative profitability of growing is favorable compared to other uses of land, which includes the U.S. in these scenarios.

Figure 3: 2050 corn production and trade by scenario. S, supply; D, demand.



In contrast, when the U.S. also undertakes a climate policy, its biomass exports are reduced and, indeed, exports may turn to substantial imports. Climate policy in the U.S. increases the domestic demand for biomass. Higher demand pushes the biomass price higher, and hence the domestic biomass production is increased. However, although domestic biomass production responds in kind, it does not, in the cases explored here, respond sufficiently to maintain the same biomass trade balance as was the case without climate policy.

The degree to which the U.S. exports or imports biomass depends heavily on the stringency of the climate policy and the nature of the competing technological options for reducing emissions in the U.S. Not surprisingly, higher stringency of U.S. policy leads both to greater domestic biomass production and greater biomass imports. Ultimately, there are diminishing marginal returns on the production of domestic biomass (as well as on any land use), so that it cannot grow at the same rate as demand. Several of the 50% abatement cases include biomass imports by 2050; in all of the 80% abatement cases the U.S. is a heavy importer of biomass.

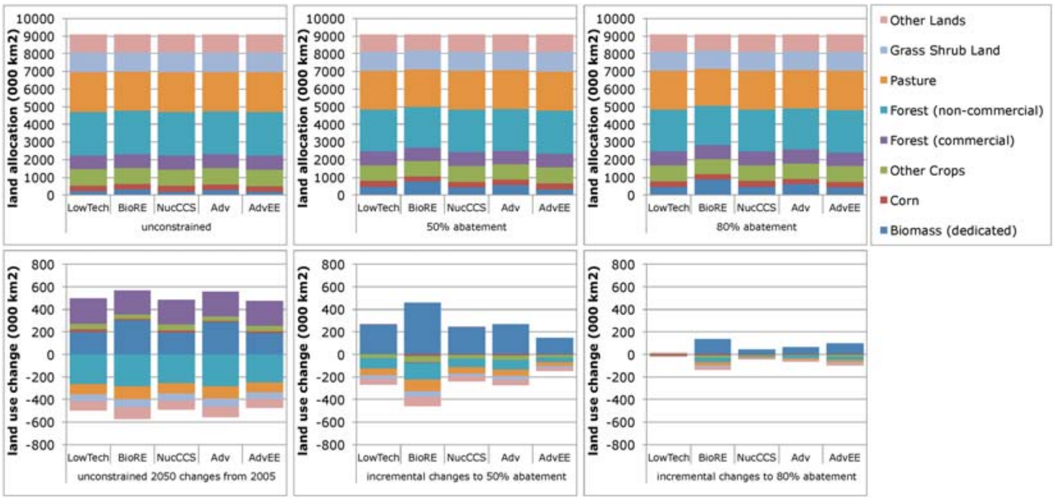
The first order effect of technology assumptions on the biomass trade balance is essentially just to alter the level of biomass demand, all else equal. When other low carbon energy options, such as nuclear or CCS, are readily available, the demand for biomass is lower. Hence, at a 50% abatement level, the U.S. does not need to import biomass when nuclear and CCS are both available. On the other hand, biomass imports are largest when the pressure to use biomass is increased due to limited availability of other technology options (LowTech) or when global biomass supply is plentiful and advanced bioenergy technologies exist, favoring the use of bioenergy as a major abatement option (BioRE).

4.3. Corn production and trade

Dedicated lignocellulosic biomass crops such as switchgrass ultimately compete with other agricultural crops for land. Hence, if biomass demands and production are altered through climate policy, the expectation is that there should be effects on the other crops against which biomass competes. Here we focus our results discussion on corn as emblematic of U.S. crop production and exports. (Figure 3).

In general, the influence of U.S. climate policy on corn production and exports is relatively modest. The U.S. was a heavy exporter of corn in 2005 and remains a heavy exporter in 2050 across the GCAM scenarios assuming no climate policy in the U.S. (the left panel in Figure 3). There are some variations in domestic corn production and in the amount of corn exports, but the general tendency to export is robust across different technology scenarios.

Figure 4: U.S. 2050 land allocation (upper) and incremental land use change relative to the less stringent scenario (lower) by scenario.



Continuation of corn exports is preserved in all but one abatement scenario. The sole exception is the LowTech 50% abatement scenario where the U.S. becomes a slight net importer of corn. In the absence of other major abatement options (LowTech), the conventional corn ethanol becomes one of the few remaining abatement options for the U.S., and this contributes to the U.S. to become a net importer of corn.

In other cases, as the abatement level becomes more stringent, overall corn production is decreased due to increased land area needed to produce lignocellulosic biomass crops. The combined effect on corn net exports is ambiguous. It depends on the relative magnitude of reduction in production and consumption. The magnitude of reduction in production, in turn, depends on the comparative advantage of corn and biomass production in the U.S. and in the rest of the world. And the magnitude of reduction in consumption depends on the combined elasticity of the demand response of corn consumption for feed, food, ethanol, and other uses. Among the scenarios considered, we generally observe a decreasing amount of net exports of corn with respect to abatement level. However, the effect is rarely strong enough to make the U.S. a net importer of corn.

4.4. Land allocation and land use change

Ultimately, changes in U.S. production of corn and biomass are determined by the amount of land devoted to each, as well as to other crops or uses of land (Figure 4). Without a domestic climate policy (the left panels in Figure 4), the U.S. devotes more land to biomass, to corn, to other crops, and to commercial forest land. As the world economies and populations continue to grow, there is more demand for the agricultural and forest products, as well as an increased demand for bioenergy in those countries undertaking climate mitigation. This will tend both to increase the demand for bioenergy in general, and also supplant other productive uses of land in those countries that are undertaking climate mitigation. As a result of increasing production of these tradable products, the U.S. decreases the amount of land in unmanaged uses (non-commercial forest, grass and shrubland, other lands) as well as pasture lands not used for grazing.

The introduction of a constraint on emissions in the U.S. further increases the demand for bioenergy, and therefore increases the biomass production in the U.S. (the middle and right panels of Figure 4). The incremental change in land use (the bottom middle and right panels of Figure 4) is almost entirely due to an increase in biomass production over the reference or no-policy case. It is interesting to note that the incremental effect of the 50% reduction scenario (the bottom middle panel of Figure 4) is substantially larger than the incremental effect of moving from a 50% reduction to an 80% reduction scenario (the bottom right panel of Figure 4), indicating diminishing marginal returns to expansion of cropland for biomass and other crops. After meeting the first 50% abatement constraint, it requires substantially larger change in profitability to expand into the remaining lands.

The magnitude of this substitution depends highly on the technology development pathways. As noted above, all else equal, the availability of other advanced technologies reduces the magnitude of substitution (e.g. NucCCS and AdvEE). On the other hand, the availability of advanced biomass technology increases the magnitude (e.g. BioRE).

5. RESULTS: IMPLICATIONS OF FOREST PROTECTION AND BIOMASS TRADE RESTRICTIONS

In the previous section we observed two important potential influences of U.S. domestic climate policy related to biomass production and consumption. One issue was an increased reliance on imported biomass. A possible remedy for these issues is to restrict biomass imports; in other words, all biomass used for abatement in the U.S. energy sector must come from a domestic source. Such policy could be proposed based on inability to control indirect emissions outside the U.S. jurisdiction, or based on a desire to limit energy imports. Another, and related influence of U.S. policy is deforestation from land use change. Deforestation results in CO_2 emissions from land use change, at least partially offsetting the original purpose of climate policy.

To address these two concerns, we introduce two new sets of constraints on the scenarios. The first of this is the introduction of an alternative trade regime where the trade of biomass is restricted to only allow domestic supply in the U.S. ("restrict"). In contrast, the baseline assumption of GCAM is that biomass is grown where its relative profitability is favorable, and it is traded freely across national boundaries ("trade"). The second constraint is a forest protection policy, in which all non-commercial forested land in the base year 2005 must be kept as forests indefinitely. There are two scopes of the forest protection policy: "USA protect" and "Global protect", as well as a baseline "not protect" case.

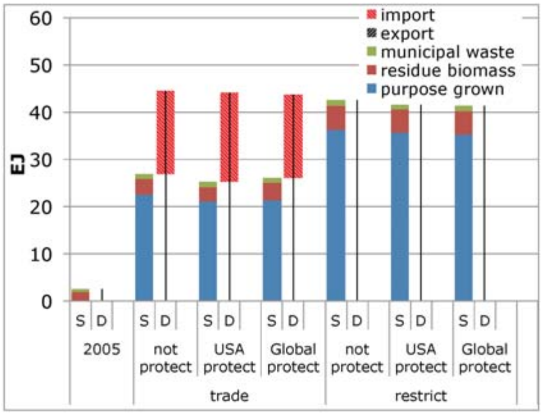
To maintain a reasonable scope for this additional analysis, we focus here only on a single scenario: the advanced technology scenario with 80% abatement constraint. Using this scenario, we overlay the two additional sets of constraints (see Table 1). All six combinations of trade regimes and forest policies are compared in this section.

5.1. Biomass production and trade

The immediate effects of the additional constraints are first observed in the biomass market (Figure 5). Trivially, biomass trade restrictions forces net imports of biomass to be zero. The market equilibrium effect of this policy is two-fold: domestic biomass supply substantially increases, and domestic demand slightly decreases.

The balancing of the domestic biomass market relies heavily on the large increase in supply, not on decrease in demand. Given the availability of suitable arable lands in the U.S. for

Figure 5: 2050 biomass production and trade under 80% abatement scenarios with advanced technology. Emphasis on land use policies and biomass trade restrictions. S, supply; D, demand.



growing additional biomass and the ability to import the foregone production of other crops from overseas, the long-run supply of domestic biomass can be highly flexible (also see, Figure 8)

On the other hand, the small decrease in demand represents the level of stringency of the abatement constraint. At the 80% abatement level, each and every abatement option is valuable so that biomass energy will be used even at a high price. This effect is better demonstrated with the market price effect in Figure 7.

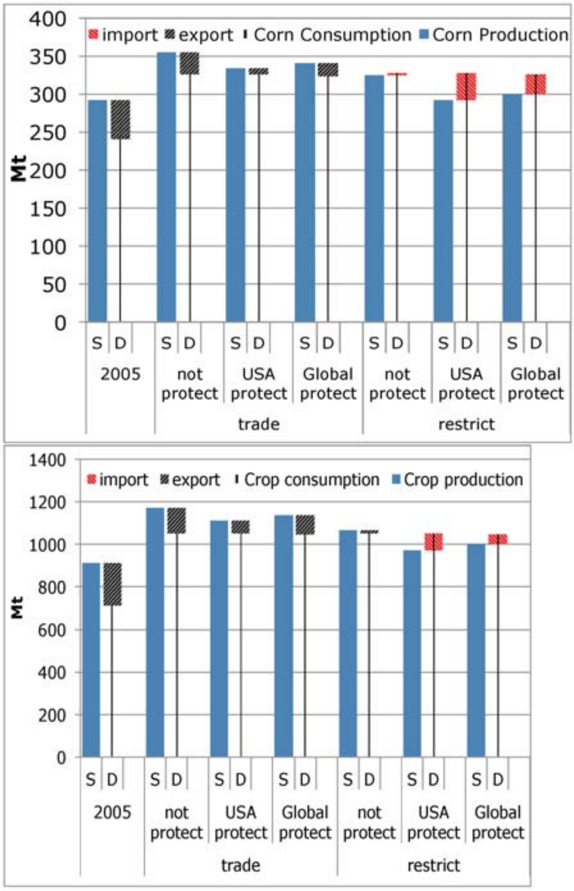
The effect of forest protection policies on biomass trade is consistent with intuition (see Figure 5). Under the free trade regime, protecting domestic forest lands results in higher pressure in current agricultural land that results in reduced production of all crops including biomass, relative to reference case future levels. The reduced domestic production is made up by a combination of increased imports from the regions without forest protection policy and decreased consumption. When the forest protection is applied globally, the competition for agricultural land becomes stronger in all regions, and as a result the biomass import is reduced. The decrease in global production is made up by a combination of increased U.S. domestic production and decreased consumption.

A similar effect due to forest protection is observed under the restricted biomass trade policy. Protecting domestic forest results in reduced future production of all crops, including biomass, relative to reference case values. The reduced domestic biomass production is only matched by reduced domestic consumption, since biomass imports are restricted. When the forest protection is applied globally, the pressure on agricultural land becomes stronger in all regions, and since biomass import is not an option, this pressure on land competition results in further reduced domestic production and consumption of biomass.

5.2. Corn and other crop production and trade

The constraints on imports and forest protection policies cause ripple effects to other crops that compete with biomass. In addition to using corn to illustrate these effects, we also present results for total non-biomass crop production (Figure 6). Recall that at the 80% abatement constraint, all technology scenarios showed a decrease in U.S. corn exports, although it still maintained a net-

Figure 6: 2050 corn (top panel) and total crop (bottom panel) production and trade under 80% abatement scenarios with advanced technology. Emphasis on land use policies and biomass trade restrictions. S, supply; D, demand.

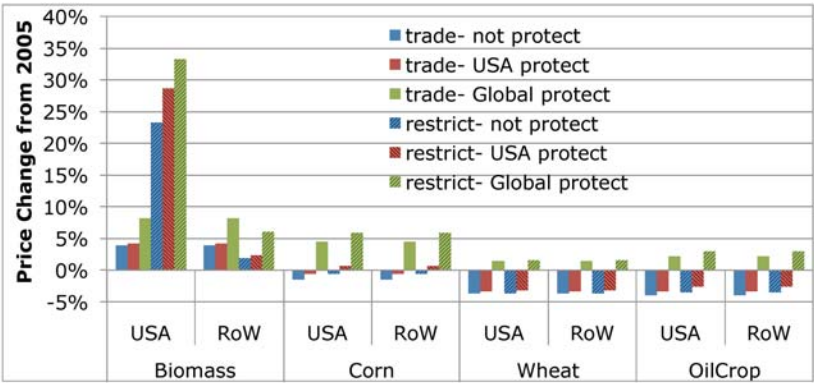


exporter status. This is still true – though at an ever smaller size of net exports – under any forest protection policies as long as biomass is freely traded. However, notice that under the restricted biomass trade regime, the U.S. becomes a net importer of corn.

The biomass trade restriction increases the pressure to grow more biomass domestically. In order to do so, portions of other cropland are converted for biomass production. As a result, domestic production of corn is reduced as we enforce biomass trade restriction. Biomass production competes against all crops for land use, and a similar effect is seen on other crops as well. In order to fulfill the domestic demand, some corn, as well as some amount of other crops, must be imported. Depending on the share of converted land area and comparative advantage, the net export of a crop may be merely reduced or net import of a crop may be further increased, but in this specific combination of abatement level and technology, the corn trade balance coincidentally turns from net export to net import. However, the direction of the effects of biomass trade restriction on *non-restricted* crop trade balances is unambiguously negative.

Domestic forest protection policies further increase competition for agricultural land use, and result in a smaller domestic corn production. The effect is similar for both trade regimes. With

Figure 7: 2050 crop price change under 80% abatement scenarios with advanced technology. Emphasis on land use policies and biomass trade restrictions. RoW, rest of the world.



little change in domestic demand, the differences in production directly results in reduced net export under free trade regime and increased net import under restricted biomass trade regime. When the forest protection is applied globally, this effect is reversed. As the land available for crop production is reduced in the rest of the world, some supply that provided imports of crops from the rest of the world is no longer available, resulting in a higher domestic supply of crops, including corn.

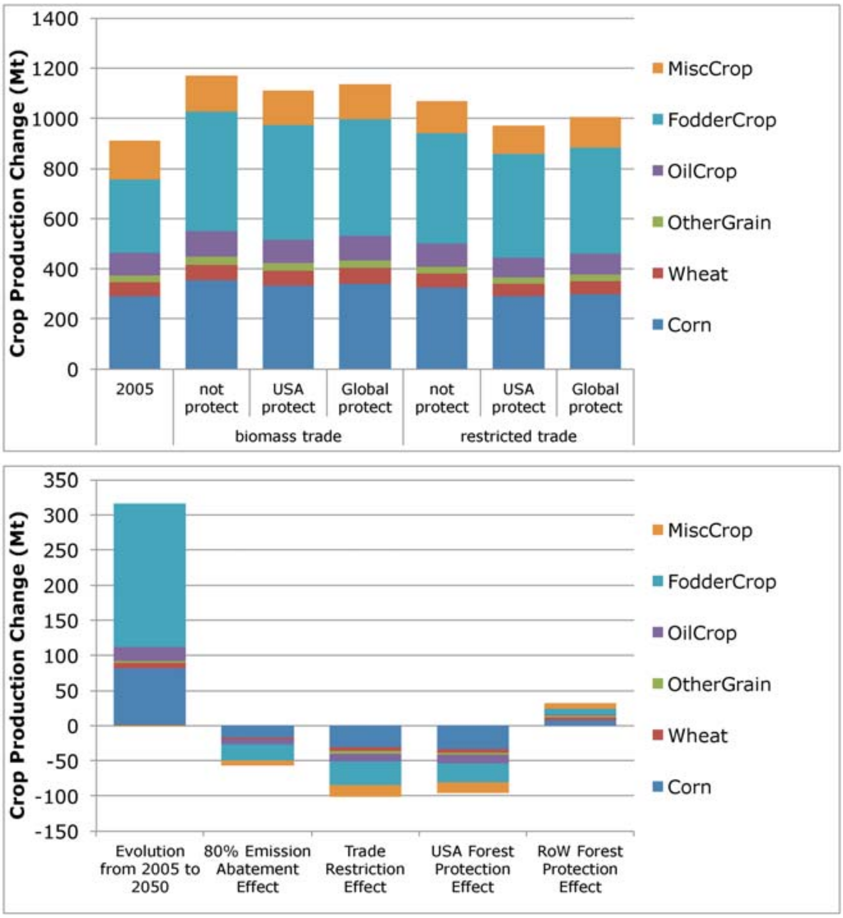
5.3. Crop prices

The crop price changes shown in Figure 7 help illustrate the dynamics of pressures on land competition from the biomass trade and forest protection policies. A trade restriction, by definition, creates two different markets with two different prices for the same good (here, biomass). With the stringent abatement constraint, the U.S. would have been a net importer of biomass in the absence of a trade restriction. But as the trade restriction is introduced, the price of the U.S. biomass increases to provide incentives for domestic growers to switch to biomass production. In an opposite effect, the introduction of the trade restriction leaves the rest of the world with more biomass, which then drives down the market-clearing price outside of the U.S.

Because we assumed free global trade of all of the crops shown, all the other crops have the same price for the U.S. and the rest of the world. The trade restriction reduces economic efficiency in the world biomass markets. This inefficiency results in a large increase in price for the region and crop directly targeted for trade restriction (USA biomass), as well as smaller increases in global prices for all other freely traded crops. The differential increase in crop price makes other crops relatively less profitable to biomass in the U.S., and increased comparative advantages of other crops prevail in the rest of the world to produce more of them and either export them to the U.S. or substitute what used to be imported from the U.S. to domestic production. The combined effect is decreased net exports and increased net imports of globally traded crops in the U.S.

Forest protection policies show differential impacts on crop prices between traded crops and non-traded biomass crop. The U.S. domestic forest protection mainly affects the non-traded biomass, and shows a smaller impact on the other crops. When the competition for land is increased, biomass, the only crop that cannot be supplied from elsewhere, faces a large increase in price in

Figure 8: 2050 crop production under 80% abatement scenarios with advanced technology. Emphasis on land use policies and biomass trade restrictions.



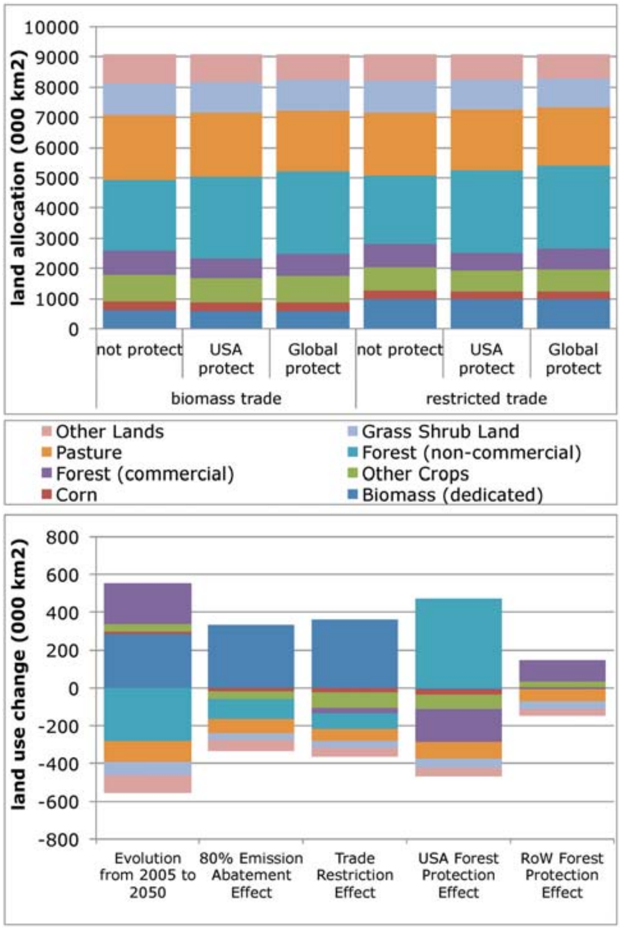
the U.S. However, when the forest protection policy is applied globally, the increased pressure on agricultural land everywhere increases all crop prices.

5.4. Other crop production and land allocation

All other major crops see the same effect as corn (Figure 8). Trade restrictions on biomass reduce production of all other crops in order to produce more biomass domestically. This effect goes beyond the croplands. All arable land types, including forest, pasture, grassland, shrubland, and so on, are decreased to provide sufficient land for increased domestic biomass production (Figure 9).

Domestic forest protection further reduces production of all other crops in order to maintain protected forest areas. The replacement effect is limited for biomass land, which is both highly restricted and valuable. Instead, the replacement is heavily focused on commercial forest and pasture, where the land has become relatively less profitable. And finally the rest of the world's implementation of a forest protection policy induces the U.S. to increase crop production to make up

Figure 9: 2050 land allocation and land use change under 80% abatement scenarios with advanced technology. Emphasis on land use policies and biomass trade restrictions.



for some of the decreased production outside of the U.S. Throughout the incremental additions of forest constraints, pasture, grass and shrub lands, and other non-commercial lands are incrementally replaced by croplands for food, biomass, and other agricultural products.

6. CONCLUSION AND DISCUSSION

This paper uses the GCAM integrated assessment model to explore the interconnected effects of biomass energy with climate policy, land use, energy, and agricultural trade. In the first part of the analysis, we observed the impacts of U.S. climate policy on agricultural trade. Implementing a domestic emission constraint increases the consumption for biomass in the U.S. All else equal, increased domestic consumption results in a net increase in biomass imports (or a net decrease in biomass exports). The precise magnitude of biomass imports depends on a number of factors, including other available abatement technologies, the stringency of domestic emission constraints, and the relative stringency of climate policies in other parts of the world.

In the second part of the analysis, we focused on one specific technology scenario and a stringent 80% abatement policy to further explore the different aspects of the issue. We modeled a biomass import restriction to address the concerns of energy imports and indirect land use change emissions. All else equal, high domestic demand for biomass coupled with the trade restrictions results in higher domestic production of biomass. When more land is used for biomass production, the domestic production of other crops decreases, which is partially offset by increased imports. A policy proposal of trade restrictions on biomass should take the indirect impact on food imports and exports into consideration.

We also explored a forest protection policy, much like that studied by Popp et al. (2012) as an additional, more direct means to address the concerns regarding land use change emissions resulting from biomass production. All else equal, a domestic forest protection policy coupled with high biomass demand puts high pressure on arable land. Physical limits on domestic cropland expansion results in further increases in crop imports. In some of the most stringent cases analyzed in this research, the U.S. becomes a net corn importer. The increased corn production in the rest of the world would also cause changes in land use patterns and corresponding changes in emissions. We included another scenario with a globally coordinated forest protection policy designed to address the issue of land use change emissions merely shifting from one country to another. In this scenario, the pressure on agricultural land increases globally and the U.S. crop imports are decreased.

Our findings from this analysis do not substantively contradict intuition. However, the value-added in building a formal model to test our hypotheses is in providing a detailed understanding of the mechanism in which our hypotheses materialize. While these scenarios are intentionally developed to illustrate the extreme in the broad range of plausible policy environments, it is worth noting the unintended consequences quantified here. The modeling results do not show or imply that these impacts on biomass and food crop trade themselves are negative, but instead that they may exist.

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REFERENCES

Chum, H., A. Faaij, J. Moreira, G. Berndes, P. Dhamija, H. Dong, B. Gabrielle, A. Goss Eng, W. Lucht, M. Mapako, O. Masera Cerutti, T. McIntyre, T. Minowa and K. Pingoud (2011). "Bioenergy." In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://dx.doi.org/10.1017/CBO9781139151153.006.

Clarke, L., A. Fawcett, J. McFarland, J. Weyant and Y. Zhou (this volume). "Technology and U.S. Emissions Reductions Goals: Results of the EMF 24 Modeling Exercise." *The Energy Journal.*

Clarke, L., J. Lurz, MA Wise, JA Edmonds, SH Kim, SS Smith and HM Pitcher (2007). *Model Documentation for the MiniCAM Climate Change Science Program Stabilization Scenarios: CCSP Product 2.1a*. PNNL Technical Report. PNNL-16735.

Edmonds, J. and J. M. Reilly (1985). *Global energy: assessing the future,* Oxford University Press.
Fargione J, J Hill, D Tilman, S Polasky and P Hawthorne (2008). "Land Clearing and the biofuel carbon debt" *Science*, 319:1235–1239. http://dx.doi.org/10.1126/science.1152747.
Fawcett, A., L. Clarke, S. Rausch, and J. Weyant (this volume). "Overview of EMF 24 Policy Scenarios." *The Energy Journal.*
Hamelinck, C. N., R. A. A. Suurs and A. P. C. Faaij (2005). "International bioenergy transport costs and energy balance." *Biomass and Bioenergy*, Volume 29(2): 114–134, ISSN 0961-9534.
Havlík, P., Schneider, A.U., Schmid, E., Böttcher, H., Fritz, S., Skalský, R., Aoki, K., de Cara, S., Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A, Sauer, T. and Obersteiner, M. (2011). "Global land-use implications of first and second generation biofuel targets." *Energy Policy* 39: 5690–5702. http://dx.doi.org/10.1016/j.enpol.2010.03.030.
Kyle, G. Page, Patrick Luckow, Katherine Calvin, William Emanuel, Mayda Nathan, and Yuyu Zhou (2011). GCAM 3.0 Agriculture and Land Use: Data Sources and Methods. Pacific Northwest National Laboratory. PNNL-21025. http://wiki.umd.edu/gcam/images/2/25/GCAM_AgLU_Data_Documentation.pdf
Luckow, P., M. A. Wise, J. J. Dooley and S. H. Kim (2010). "Large-scale utilization of biomass energy and carbon dioxide capture and storage in the transport and electricity sectors under stringent CO2 concentration limit scenarios." International Journal of Greenhouse Gas Control, Volume 4(5): 865–877, ISSN 1750-5836. http://dx.doi.org/10.2172/973408.
Melillo, Jerry M., John M. Reilly, David W. Kicklighter, Angelo C. Gurgel, Timothy W. Cronin, Sergey Paltsev, Benjamin S. Felzer, Xiaodong Wang, Andrei P. Sokolov and C. Adam Schlosser (2009). "Indirect Emissions from Biofuels: How Important?" *Science*. December 2009: 1397–1399. http://dx.doi.org/10.1126/science.1180251.
Monfreda, C., N. Ramankutty and T. Hertel (2009). *Global Agricultural Land Use Data for Climate Change Analysis.* . in Economic Analysis of Land Usein Global Climate Change Policy. T. Hertel, S. Rose and R. Tol, Routledge.
Popp, A., M. Krause, J.P. Dietrich, H. Lotze-Campen, M. Leimbach, T. Beringer and N. Bauer (2012). "Additional CO_2 emissions from land use change – Forest conservation as a precondition for sustainable production of second generation bioenergy." *Ecological Economics* 74 (2012) 64–70. http://dx.doi.org/10.1016/j.ecolecon.2011.11.004.
Searchinger, Timothy, Ralph Heimlich, R. A. Houghton, Fengxia Dong, Amani Elobeid, Jacinto Fabiosa, Simla Tokgoz, Dermot Hayes and Tun-Hsiang Yu (2008). "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change," *Science*. 319:1238–1240. http://dx.doi.org/10.1126/science.1151861.
Thomson, A., K. Calvin, S. Smith, G. Kyle, A. Volke, P. Patel, S. Delgado-Arias, B. Bond-Lamberty, M. Wise, L. Clarke and J. Edmonds (2011). "RCP4.5: a pathway for stabilization of radiative forcing by 2100." Climatic Change, Volume 109(1): 77–94, ISSN 0165-0009, DOI:10.1007/s10584-011-0151-4.
United Nations (2008). Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (UN-REDD). http://www.un-redd.org/Portals/15/documents/publications/UN-REDD_FrameworkDocument.pdf.
U.S. Department of Energy (2011). *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*. R.D. Perlack and B.J Stokes (Leads), ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN. http://bioenergykdf.net.
Wise, M. A., K. Calvin, G. P. Kyle and P. Luckow (2011). "GCAM 3.0 Agriculture and Land Use Model Data Documentation." PNNL-20971.
Wise, M., K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S. J. Smith, A. Janetos and J. Edmonds (2009). "Implications of Limiting CO2 Concentrations for Land Use and Energy." *Science*, Volume 324(5931): 1183–1186 DOI:10.1126/science.1168475.