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The Land-Use Consequences of Woody Biomass with More Stringent Climate Mitigation Scenarios

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Abstract

Integrated assessment models increasingly rely on biomass for energy with ever more stringent mitigation policies. The stringency of mitigation will therefore have large effects on land use. As discussed in the literature, crop bio-energy will lead to substantial pressure to increase deforestation. This paper consequently explores using woody biomass for bioenergy. The paper combines the IAM WITCH with a global dynamic forestry model GTM to determine the optimal size of the woody biomass market, the effects on the timber market, and the resulting forestland under two alternative mitigation strategies. This paper predicts that moving from a moderate to a stringent mitigation policy would increase the demand for woody biomass from 3.7 to 5.2 billion m^3/yr, increasing forestland by 1049 to 1890 million ha, and shrinking farmland by 748 to 1550 million ha. The stringency of mitigation will therefore have large effects on land use.

Keywords

Climate Change, Forestry, BECCS, Land Use, Integrated Assessment Model

1. Introduction

Integrated assessment models (IAMs) suggest that biomass energy is an important mitigation technology to reach stringent climate targets. Numerous studies rely on bio-energy combined with CO_2 capture and storage technology (BECCS) to reach long run low radiative forcing targets such as 2.6 W/m^2 to limit global warming to 2˚C [1]. Without BECCS, studies suggest that the cost of stringent mitigation policies will escalate dramatically [2] [3] [4]. BECCS is particularly attractive because of its ability to reduce concentrations of CO_2 already in the atmosphere allowing more flexibility in mitigation plans [4] [5] [6].

Many IAMs assume that biomass supply will come from crops [7]. For example, some models assume that they can use low productivity grasslands for biomass. However, it is very expensive to collect biomass across low productivity lands because there is very little production per ha. Alternatively, other IAMs assume that high productivity cropland will be used to grow biomass. However, the opportunity cost of prime cropland is very high and will increase sharply as more and more land is diverted. As the price of prime cropland rises sharply, landowners around the world will clear extensive additional forestland for cropland [8] [9] [10] [11]. The resulting loss of carbon stored in forests substantially reduces the effectiveness of crop based BECCS. This study consequently focuses on the use of woody biomass to support BECCS and explores the resulting land use implications.

The existing literature on regional and national forests in the United States [12] [13] [14] and Europe [15] [16] reveals that a large increase in the demand for woody biomass would compete for forest output with traditional timber products (including paper), increase demand for forest output, increase the price of forestland, and cause forests to expand. However, regional and national studies cannot capture price effects felt through global markets. A few global studies have evaluated the implications of woody biomass on the forest sector [17] [18]. A limitation of these studies as well as the regional studies is that they examine arbitrary quantities of woody biomass for energy[1]. The quantities are not tied to carbon prices nor are they able to capture the price feedbacks from the energy sector to the land sector and back. Two studies have used a land use model to analyze a dynamic path for biomass in a mitigation portfolio [19] [20]. These studies examine biomass from both agricultural crops and woody biomass. However, their analyses lack a detailed description of the forestry sector which limits how accurately they capture woody biomass in their models.

This paper focuses specifically on understanding how woody BECCS affects land use by combining a detailed global, dynamic model of forests (GTM) [21] [22] [23] with a sophisticated integrated assessment model of climate and energy (WITCH) [24] [25] [26]. The combined model has been used before to demonstrate the effectiveness of woody biomass to support both BECCS and forest carbon sequestration [27]. However, this previous analysis did not focus on the land use effects of BECCS or on how land use changes with the stringency of the mitigation target. In this analysis we compare the land use consequences of two alternative mitigation strategies, a modest policy targeting 2.9˚C and a more stringent policy targeting 2.3˚C.

[1][17] used the biomass energy projections developed for IPCC for the story lines A2 and B1. [18] used the biomass energy projections developed for IPCC for the story line A1B and RPA forest assessment. [13] used the biomass energy demand from the US Department of Energy, Annual Energy Outlook 2010. [15] used the biomass energy projections developed for IPCC for the story lines A1 and B2. [12] used the biomass energy projections developed for IPCC for the story lines A1B, A2 and B2. [14] used the projections of biomass demand developed from the baseline projection of regional bioenergy consumption from 2010-2035 in the 2010 Energy Information Administration Annual Energy Outlook.

This article is organized as follows. Section 2 introduces both models and describes the soft link between them in more detail. In Section 3, we analyze the results of the two models under alternative mitigation scenarios. We explore the desired size of the woody biomass market, and the resulting size of forestland and farmland. We also project the impacts on both the industrial timber market and agricultural output. Finally, Section 4 summarizes the results and discusses the policy implications.

2. Method

We rely on a soft link between WITCH and GTM [27]. GTM has been soft linked with integrated assessment models before to calculate optimal sequestration programs [23] [28] and to assess the optimal combination of forest sequestration and woody BECCS [29].

WITCH calculates global consumption per capita (income) and the quantity of woody biomass demanded in each time period. We then introduce these values for each time period into GTM and determine the price required to supply the global quantity of wood. This price is then reintroduced to WITCH which solves for a new quantity demanded. Again, this new quantity is introduced back into the forestry model (**Figure 1**). The two models are assumed to be linked when the quantity of woody biomass demanded by WITCH changes less than 5% between iterations. The equilibrium is achieved after 12 - 20 interactions depending on the policy scenario. This equilibrium is actually a set of distinct equilibrium conditions in each time period. The forestry model also predicts the price of industrial wood products, forestland area, and the carbon sequestered in those forests over time.

The forestry model assumes that wood products are traded in a global market so that there is one international price for wood at each moment in time [30] [31]. Prices are allowed to change over time. Demand and supply equilibrate at the global scale. Demand and supply are not constrained within any region: trade is permitted across regions so biomass does not have to be produced in the region it is consumed. WITCH has 5-year time steps and the forestry model has 10-year time steps. To link the two models, we average the 10 years biomass price steps from GTM to yield 5 year price steps for WITCH.

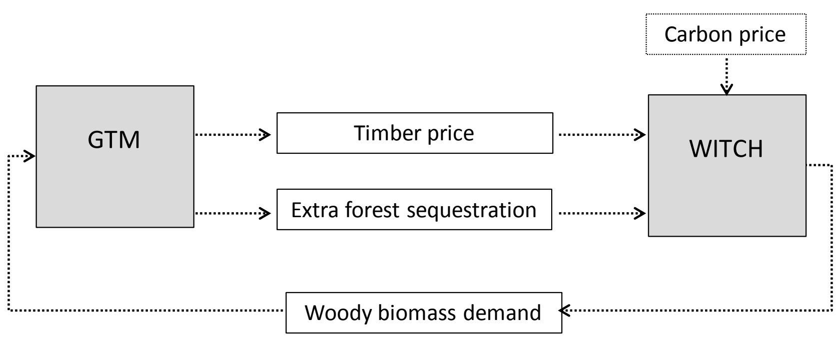


Figure 1. Soft-link of WITCH and GTM.

We assume that only wood can be used to meet the demand for biomass. Neither biomass from crops nor biomass from forest residues (branches and leaves normally left at the forest site) is included. On average, 1 m^3 of timber produces approximately 8.8 MMBtu of energy [14] [27]. The carbon content of woody biomass is included in WITCH: we assume that on average 1 Twh of bio-energy releases 0.16 Mt C previously stored during the growth of trees and produces extra sequestration[2] of 0.10 Mt C in soil, slash and market products.

We assume that woody biomass is used only in integrated gasification combined cycle (IGCC) power plants with CCS[3]. Technically, residences also use woody biomass for heat and cooking but we assume this use remains fixed over time and across policies. The efficiency of the IGCC power plants is assumed to be 35%. Carbon capture and storage technology is assumed to be able to capture 90% of emissions [26]. That is, 90% of above ground carbon stored during the growth of the trees and then released at the burning time will be captured and sequestered via CCS. Finally, the capital cost for biomass-fired IGCC power plants is assumed to be 4170 USD/kW. The cost of storing CO_2 underground is region-specific, it varies according to the estimated size of reservoirs and it increases exponentially as cumulative storage increases [26].

The baseline scenario is a Business As Usual (BAU) scenario with no greenhouse gas mitigation policies over the century. Average global GDP per capita is assumed to grow from 6900 USD in 2005 to 18,000 USD in 2050 and to 39,634 USD in 2100. Global total primary energy supply grows from 436 EJ/yr in 2005, to 820 EJ/yr in 2050, and to 1013 EJ/yr in 2100. GHG emissions are equal to 44 Gt CO_2 in 2005, 80 Gt CO_2 in 2050, and 101 Gt CO_2 in 2100. This corresponds to a level of GHG concentration in the atmosphere in 2100 of 951 ppm, radiative forcing equal to 6.6 W/m^2, and warming of 4˚C [33].

The paper explores two mitigation scenarios that lead to 630 ppm and 530 ppm concentrations of GHGs. These are predicted to increase radiative forcing to 4.3 and 3.4 W/m^2 respectively, leading to expected global warming of 2.9˚C and 2.3˚C respectively relative to pre-industrial levels. WITCH predicts how the demand for biomass would change over time depending upon the mitigation scenario. GTM predicts how forest management, forest stocks, and forestland change over time to provide timber supply. Together these two models predict the efficient amount of woody biomass supplied for mitigation and the resulting effects on land use. We solve WITCH using a global carbon price. Carbon prices force mitigation to be cost effective across sectors and countries providing when and where flexibility. WITCH solves for the optimal level and growth rate of the carbon price given the target concentration. WITCH predicts the carbon price

[2]The extra carbon sequestration is defined as the difference between the amount of carbon stored in forests' soil and slash and wood products in the baseline scenario and the amount of carbon stored in forests' soil and slash and wood products in the policy scenario.

[3]Several test runs have shown that when the CCS technology is available there are no incentives to use biomass in standard pulverized coal power plants without CCS. For this reason we describe the model assuming that biomass is used only in IGCC power plants with CCS.

would be 4 and 14 USD/tCO_2 in 2020 for the moderate and stringent targets and would reach 335 and 1059 USD/tCO_2 in 2100 in the two scenarios. We assume that no effective forest sequestration policies (other than carbon capture and storage) are available in this analysis[4].

3. Results

3.1. Woody Biomass Market

We assume that using woody biomass for energy is carbon neutral. That is, we assume that the carbon released during combustion is offset by the carbon captured during the growth of the trees (this is not exactly correct because the storage occurs over a long time before the release)[5]. In addition, we assume that biomass power plants receive credits for the average extra forest sequestration[6] they encourage [27]). Given these assumptions, higher carbon taxes make woody biomass more attractive relative to fossil fuel. With the BAU scenario, carbon prices are effectively zero which leads to minimal use of woody biomass for energy (only wood residues at mills would be used). In order for companies to use wood for fuel, the carbon price must be about 84 USD/tCO_2. Even with the relatively stringent mitigation program, woody biomass is not used as fuel until 2040. With the more moderate scenario BECCS is first introduced in 2055. However, by 2100, BECCS are predicted to generate 6% - 12% of global electricity. As carbon prices rise over time, there is an ever increasing demand for woody biomass each decade. Consequently, cumulative use of woody biomass also increases with stringency. Going from the 2.9˚C to the 2.3˚C target increases the demand of woody biomass from 3.7 to 5.2 billion m^3/yr in 2100 (**Figure 2**).

3.2. Wood Price and the Industrial Timber Market

As mitigation policies become more stringent, there is a huge shift in the demand for wood. This leads to a rapid increase in the international price of wood depending on the scenario. Our forward looking model plants and grows the timber that is eventually needed. Because this wood is grown before it is used, the effect of the biomass burning in the second half of the century is seen as early as 2040. Already by 2040, the price of wood increases by 4% - 54% (depending on the scenario) relative to the BAU scenario. By 2100, wood quadruples in price to almost 780 USD/m^3 for the moderate scenario and 1830 USD/m^3 in the stringent scenario (**Figure 3**).

These changes in price encourage a large expansion of total timber production in the second half of the century. In the BAU scenario (no woody biomass for BECCS), total global production reaches 2.6 billion m^3/yr by 2100. However, in the stringent scenario, total global timber production more than doubles by 2100 to 5.5 billion m^3/yr. Despite this huge increase in wood supply, competition with

[4][34] argue why effective forest sequestration policies may be difficult to implement in practice.

[5]For simplicity this analysis ignores ancillary fossil fuel emissions associated with biomass harvest and transport.

[6]We assume power plants receive a subsidy equal to the carbon tax for each extra ton of carbon permanently stored in standing forest, slash, or soil.

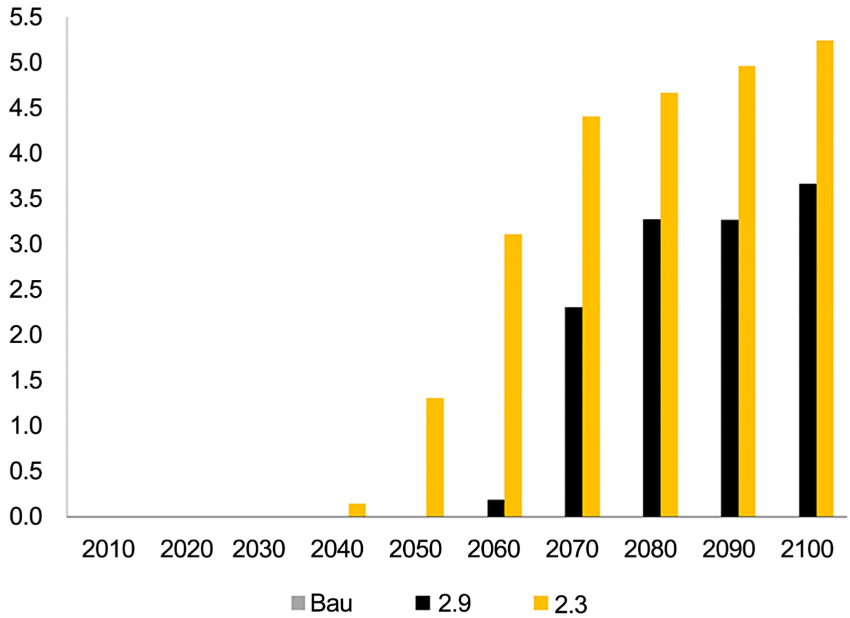


Figure 2. Woody biomass for energy the global level 2010-2100 under the 2.9˚C and 2.3˚C mitigation policy scenarios (billion m^3/yr).

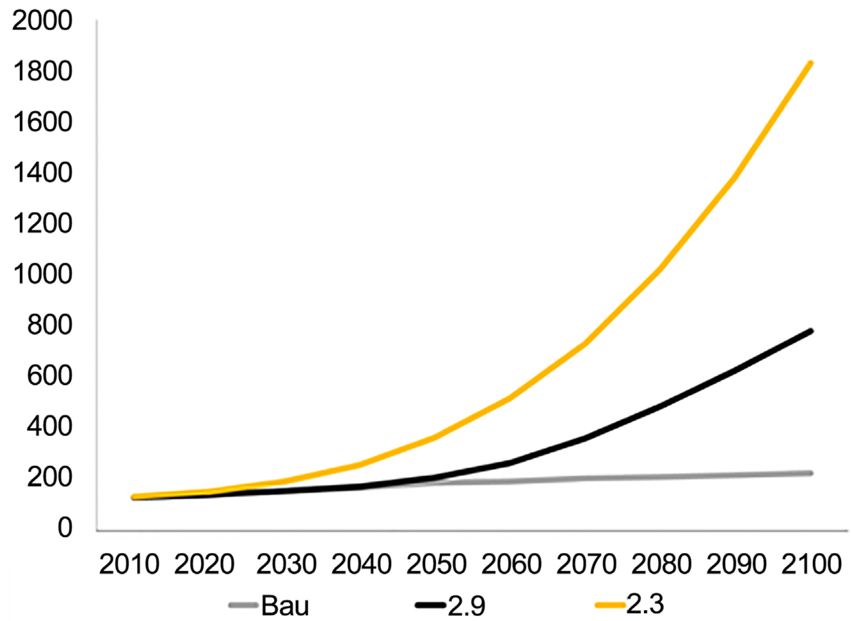


Figure 3. International price of wood under the BAU scenario and the 2.9˚C and 2.3˚C mitigation policy scenarios (USD/m^3).

BECCS causes the traditional industrial wood sector (sawtimber and paper) to shrink. By 2100, industrial wood demand falls to 0.2 billion m^3/yr in the stringent scenario and 0.6 billion m^3/yr in the moderate scenario (**Figure 4**).

Although using woody biomass helps address needs of the energy sector, it would have huge impacts on the saw timber and pulp and paper sectors. Almost all of this effect is due to the high price of wood (there is also a small income

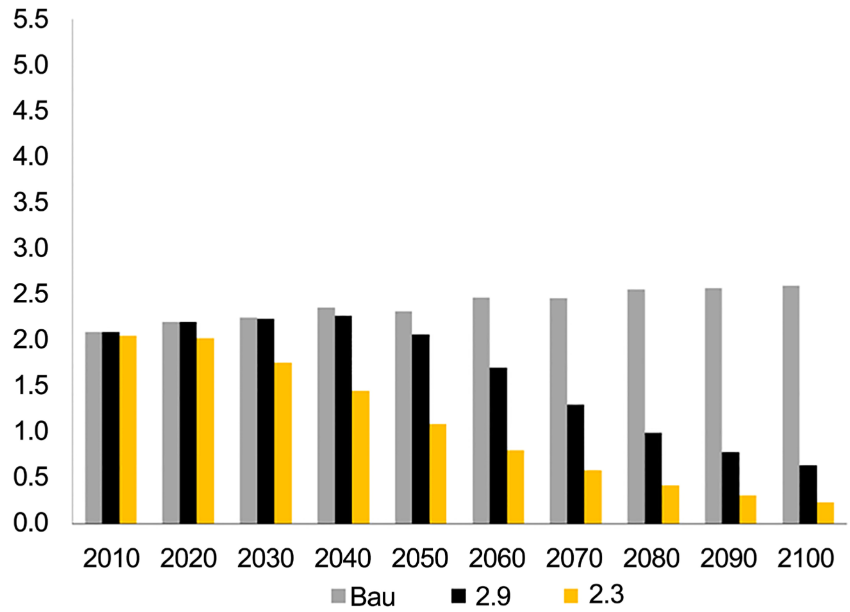


Figure 4. World industrial timber production under the BAU scenario and the 2.9˚C and 2.3˚C mitigation policy scenarios (billion m^3/yr).

effect from the reduction of global consumption per capita[7]). The stringent mitigation policy causes the demand for woody biomass to become more price inelastic than the demand for industrial wood causing a large substitution from sawtimber and paper to energy.

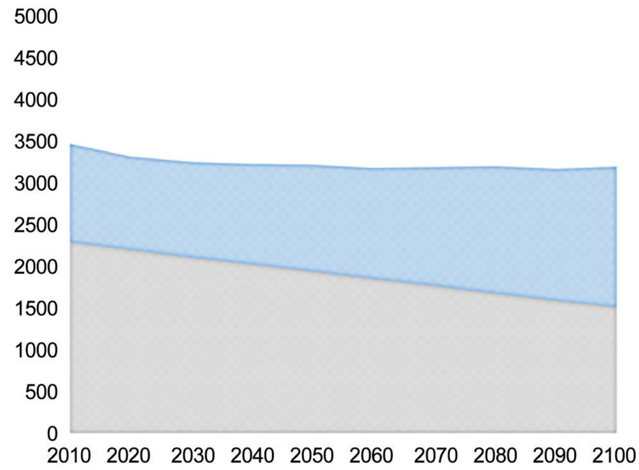
3.3. Forest Land

In order to support the large increase in wood supply, forestland expands dramatically (**Figure 5(a)**). In the BAU scenario, global forestland remains somewhat constant over the century at 3500 million ha. As mitigation increases, the increasing demand of woody biomass requires considerably more managed forestland both over time and across scenarios (**Figure 5**). Because the model is forward looking, managed forestland expands before biomass is actually burned in great quantities. Already by 2040, managed forestland has expanded by 30% - 60% relative to the BAU depending on the scenario. Relative to the BAU scenario, managed forestland has expanded by 1050 million ha in the modest scenario and by 1890 million ha in the stringent scenario. Some of this land will come from natural forestland (**Figure 5(c)**) and the rest from farmland. Farmland is expected to shrink by 750 million ha and 1550 million ha respectively[8]. Because of the high opportunity cost of using prime cropland, most of this lost farmland is likely to be marginal (pasture and cropland for livestock fodder).

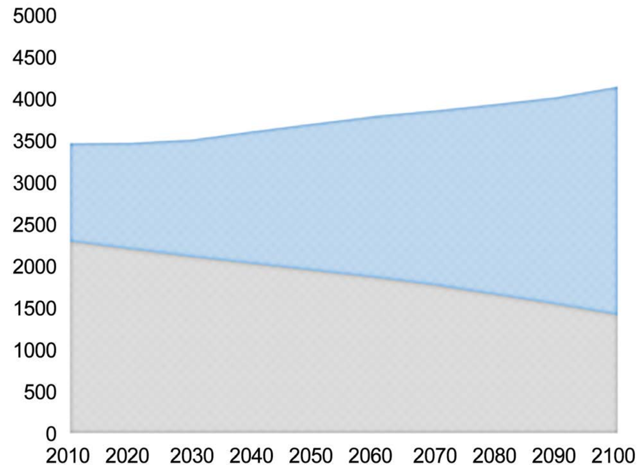
Thus, the impact of mitigation on global land use can be very large. As the

[7]The introduction of the carbon tax will reduce the world consumption per capita by 0.6% - 2.1% in 2050 and by 2.6% - 9.7% in 2100 with respect to the baseline scenario.

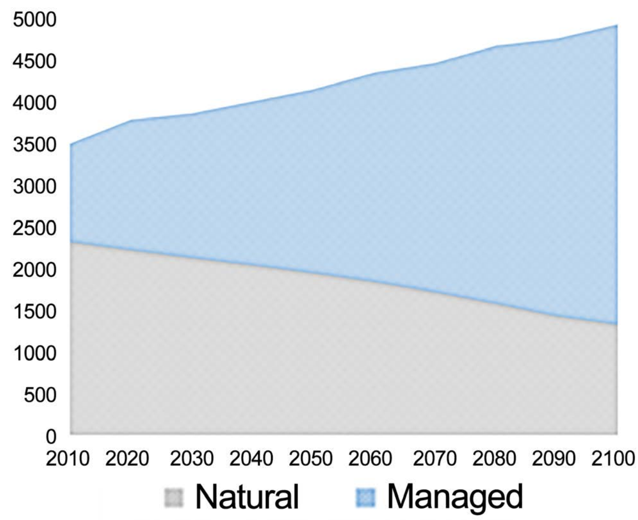
[8]In 2011 global permanent meadows and pastures land was about 3400 million ha and arable land and agriculture area was about 5000 million ha (http://faostat.fao.org/).



(a) BAU



(b) 2.9˚C



(c) 2.3˚C

Figure 5. (a) Forest area; (b) managed forestland; and (c) natural forestland (million ha) with the BAU, 2.9˚C and 2.3˚C mitigation scenarios.

Thus, the impact of mitigation on global land use can be very large. As the severity of mitigation increases there is ever more pressure to use both natural lands and farmland. However, the inelastic demand for food likely limits how much prime cropland that will be taken. Nonetheless, it is likely that more severe mitigation will lead to higher food prices and especially higher prices for animal products.

4. Conclusions

A wide suite of IAMs are relying on bio-energy with CCS (BECCS) to meet stringent limits. However, the IAMs do not have enough detail about global forests to make careful estimates of biomass supply over time and across regions. As a result, they are not adequate to estimate the effect of biomass demand on industrial timber demand, the international price of wood and forest land use in a dynamic framework. Integrating the complex dynamic demand for bio-energy from the IAMs with the complex dynamic structure of forests and forest supply is a daunting intertemporal task.

The aim of this paper is to provide a global, dynamic and detailed description of woody biomass supply under various climate mitigation scenarios. By linking the economic model WITCH and the forestry model GTM, we explore the resulting woody biomass market, forestland, and farmland for different mitigation policies. We specifically examine two mitigation plans that limit warming from 4.0˚C by 2100 in the uncontrolled case to 2.9˚C and 2.3˚C in 2100.

The stricter the target, the higher the resulting carbon price path. Initially, woody biomass is too expensive and is used in only special circumstances. As carbon prices rise, woody biomass becomes relatively more attractive. By the middle of the century, carbon prices are high enough to begin to switch from fossil fuels to burning woody biomass. This increases the total demand for wood significantly in the second half of the century. The more stringent policy increases the demand for woody biomass from 3.7 to 5.2 billion m^3/yr by 2100. This big future increase in demand for wood causes managed forestland to expand dramatically starting almost immediately. By 2100, managed forestland expands by 1049 million ha for the 2.9˚C mitigation strategy and by 1890 million ha for the 2.3˚C scenario. The increasing value of managed forestland will cause about 300 million ha of natural forests to become managed largely in the tropics. Although overall forests will increase, there may be conflicts of interest between conservation and woody biomass for energy.

The biggest source of new forestland will be from farmland. About 11% of farmland in the 2.9˚C scenario and 20% of farmland in the 2.3˚C scenario will be converted to managed forestland by farmers. Specifically, farmers in regions that are suitable for forests will earn more profits converting marginal farmland into managed forests. Prime cropland is likely to remain untouched by the woody biomass program because of the high value of growing crops in a world with less total cropland.

It is interesting to compare these results with other studies of bio-energy.

Some of these studies predict there would be twice as much bio-energy available by 2100 [2] [3] [5] [6] [19] [20] [32] [35]. That is, they predict that the cost of producing biomass is lower than this study. The higher supply is the result of different assumptions about the type of biomass feedstock (all of them consider both crop and wood bio-energy), the use of agricultural and forestry residues, and biomass energy output (which ranges from 100 to 400 GJ/ha/yr). The higher yields, however, are only available on prime cropland. The crop biomass programs will therefore have a large impact on the aggregate amount of prime cropland. We suspect that earlier studies have underestimated the cost of converting prime cropland to crop biomass plantations. The resulting high price of food will encourage forest landowners around the world to replace that lost prime cropland with even more hectares of new marginal farmland. The resulting conversion of forestland to marginal cropland will cause a substantial increase in carbon to the atmosphere. If using prime cropland for biomass does in fact lead to substantial deforestation, it will be far less effective than the studies assumed.

Although BECCS helps address the needs of the energy sector, it will likely also impact the wood available for the industrial sector (paper and timber). Despite the huge increase in forests and wood supply, the sawtimber, pulp and paper sectors are expected to shrink from 2.6 billion m^3/yr in the BAU to 0.2 and 0.6 billion m3/yr in each mitigation scenario by 2100. Consumers will have to go paperless and construction will need to find new materials to substitute for timber.

As the forest area expands, there will be an increase in the global stock of carbon stored in the forest of 170 - 360 $GtCO_2$ by 2100. The extra sequestration from the biomass program reveals the advantage of using woody biomass rather than crop bio-energy. While wood bio-energy increases the stock of carbon stored in the forest, crop bio-energy has the opposite effect because it would increase the relative value of cropland causing forestland to shrink [8] [9] [10] [11].

There remain some important topics to study in this field. First, the current analysis does not include forest residues (branches and leaves normally left at the forest site) in biomass supply. Because woody biomass is predicted to increase, more woody debris will be left in the woods. An important research question will be whether it is better to leave this debris in the woods or harvest it for bio-energy. Second, the analysis does not address the impact of climate change on forestland which could well influence the future supply of wood and biomass [36] [37]. Third, the analysis does not address likely changes in traditional biofuels (charcoal and wood logs). The woody biomass program may well drive out traditional biofuels in the future[9]. Finally, the analysis does not examine the response by the farming sector to having less available farmland. How much will the reduction in farmland stimulate further investments in farm productivity? All of these issues should be addressed in future research.

[9]In 2011 1.89 billion m^3 of wood was used for traditional biofuel whereas industrial roundwood was 1.58 billion m^3.

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