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Evaluating the Global Role of Woody Biomass As a Mitigation Strategy

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SUMMARY As policy makers consider stringent targets for greenhouse gas emissions, integrated assessment models are increasingly relying on biomass energy as a critical energy source. However, it is not clear how much woody biomass to expect across time and across the planet. The integrated assessment models simply do not have enough detail about global forests and arable land to make careful forecasts of biomass supply over time. 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. This study examines the market for woody biomass by combining the integrated assessment model WITCH with the global dynamic forestry model GTM. Three carbon tax schedules are used to simulate different mitigation policies that lead to radiative forcing levels of 3.7, 3.2 and 2.5 W/m^2 and a baseline scenario with no mitigation policies. WITCH determines the demand for woody biomass and GTM determines the supply of woody biomass over time. Moving from a mild to stringent mitigation policy would increase the demand of woody biomass from 8.2 to 15.2 billion m^3/yr while the international price of wood would increase 4 to 9 times relative to the baseline scenario by 2100. This would shrink the demand for industrial wood products from 80% to 90% with the biomass program. Forest area will expand by 70-95% leading to increased storage of 685-1,279 GtCO$_2$ in forest by 2100. Overall, the biomass program with the CCS technology plays a key contribution to overall GHG emission reductions in all scenarios contributing 20-27% of all mitigation for 2020-2100.

Keywords: Bio-energy, Carbon sequestration, Forestry, Integrated assessment model

JEL: Q23, Q42, Q54

1. Introduction

Burning woody biomass can play a key role in strategies to mitigate climate change. It can contribute to reducing carbon dioxide emissions by substituting for fossil fuels. Combined with carbon capture and storage, it can actually extract carbon dioxide from the atmosphere (Obersteiner et al. 2001). As policy makers consider stringent targets for greenhouse gas emissions, integrated assessment models are increasingly relying on biomass energy as a critical energy source (Clarke et al. 2009; Krey and Riahi 2009; Edenhofer et al. 2010; van Vuuren et al. 2011; Rose et al. 2012). However, it is not clear how much woody biomass to expect across time and across the planet. The integrated assessment models (IAMs) simply do not have enough detail about global forests and arable land to make careful forecasts of biomass supply over time. 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 existing literature on regional and national forests reveals that a large increase in the demand for woody biomass would compete for forest output with traditional timber products (including paper), that the increased demand for forest output will increase the price of forestland, and the relatively higher price of forestland will cause forest to expand. For example, there is a set of US models (Ince et al. 2011; 2012; Daigneault et al. 2012) and a set of EU models (Moiseyev et al. 2011; Lauri, et al. 2012) all of which confirm these results. It is also clear that this increase in forestland will cause overall carbon sequestration rates to increase (Malmsheimer et al. 2011; Havlík et al. 2011; Daigneault et al. 2012; Sedjo and Tian 2012). Note that crop bio-energy would have the opposite effect on carbon sequestration because it would increase the relative value of cropland (Fargione et al. 2008; Melillo et al. 2009; Searchinger et al. 2009; Wise et al. 2009). Although regional and national studies are adequate for showing the qualitative impacts of a woody biomass program, they do not reveal the global response.

Only a few studies have evaluated the global implications of woody biomass on the forest sector (Raunikar et al. 2010; Buongiorno et al., 2011). 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

[1] Raunikar et al. (2010) used the biomass energy projections developed for IPCC for the story lines A2 and B1 story lines.
Buongiorno et al. (2011) used the biomass energy projections developed for IPCC for the story line A1B and RPA forest assessment.
Ince et al. (2011) used the biomass energy demand from the US Department of Energy, Annual Energy Outlook 2010.
Moiseyev et al. (2011) used the biomass energy projections developed for IPCC for the story lines A1 and B2 story lines.

not tied to carbon prices nor are they able to capture the price feedbacks from the energy sector to the land sector and back. Past studies have examined the effects of requiring a specific amount of biomass but they do not evaluate whether these amounts are efficient. In order to determine how bio-energy should fit into an efficient carbon mitigation strategy, one must model whether bio-energy is more or less expensive than other mitigation alternatives. This depends on the magnitude of the biomass program since biomass will get more expensive as it competes against timber products and other uses of land. It also depends on the price of carbon which will determine the aggregate amount of mitigation desired over time. In practice, these factors change over time requiring a dynamic analysis which is partially missing in the literature.

Only two studies have followed a dynamic path in analysing the role played by biomass on a mitigation portfolio (Gillingham et al. 2008; Popp et al. 2011). Both studies use land use models and assume that bio-energy demand can be met by both agricultural crops and woody biomass. In this way they provide a broader description of the dynamic interactions between the land sector and the energy sector. However, their analyses lack a detailed description of the forestry sector which limits how accurately they capture woody biomass in their models.

This paper addresses these shortcomings in the literature by combining a detailed global, dynamic model of forests (GTM) (Sohngen et al. 1999; Sohngen and Sedjo 2000; Sohngen and Mendelsohn 2003; Daigneault et al. 2012) with a sophisticated integrated assessment model of climate and energy (WITCH) (Bosetti et al. 2006; 2007; 2009). The combined model is then used to evaluate alternative mitigation strategies from modest to severe.

WITCH calculates the global quantity demanded of woody biomass over time for each policy scenario. The quantity demanded for woody biomass from WITCH is then added to the demand for industrial wood products in GTM. The timber model then solves for the international price of wood. The price is then entered back into WITCH which generates a new quantity demanded. The two models iterate back and forth until demand equals supply. For each mitigation strategy, WITCH assures that the outcome takes into account a dynamic carbon price trajectory and the competition between woody biomass and other mitigation options. The forest model takes into account the competition between industrial wood products and woody biomass, the intensity of forest management, the competition for land between forestry and agriculture, and the price of forest products.

Ince et al. (2012) used the biomass energy projections developed for IPCC for the story lines A1B, A2 and B2 story lines.
Daigneault et al. (2012) used the projections of biomass demand are developed from the baseline projection of regional bioenergy consumption fro 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, the impact on industrial timber, the price of timber, the size of forestland, and the impact on forest sequestration. Finally Section 4 summarizes the results and discusses the policy implications.

2. Models

In this section, we present the economic model WITCH (Bosetti et al. 2006; 2007; 2009) and the forestry model GTM (Sohngen et al. 1999; Sohngen and Sedjo 2000; Sohngen and Mendelsohn 2003; Daigneault et al. 2012) that have been used for this analysis. We then describe the soft-link and the assumptions behind both models. Finally, we introduce the policy scenarios.

2.1. The energy–economy–climate model WITCH

The WITCH – "World Induced Technical Change Hybrid" – model is a regional integrated assessment model structured to provide normative information on the optimal responses of world economies to climate damages[2] (cost-benefit analysis) or on the optimal responses to climate mitigation policies (cost-effectiveness analysis) (Bosetti et al. 2006; 2007; 2009).

WITCH has a peculiar game-theoretic structure that allows modelling both cooperative and non-cooperative interactions among countries. As in RICE (Nordhaus and Yang 1996), the non-cooperative solution is the outcome of an open-loop Nash game: 13 world regions interact non-cooperatively on fossil fuels, energy R&D, and on learning-by-doing in renewables. In this work we use the non-cooperative solution to build both the baseline and the policy scenarios. The economy of each region is modeled along the lines of a Ramsey-Cass-Koopmans optimal growth model. The model is solved numerically assuming that a central planner governs the economy.

The economy is composed of three sectors: (i) the sector that produces the final consumption good; (ii) the oil extraction sector (Massetti and Sferra, 2010) and (iii) the power sector. For this analysis we focus on the power sector. Firms in the power sector generate electricity using ten different technologies: oil, coal, gas, nuclear, wind, hydropower, biomass, coal with carbon capture and storage (CCS), gas with CCS, biomass with CCS. The choice of investments in power generation

[2] WITCH has a damage function that translates global mean temperature in productivity impacts to the final good sector. Although, in this paper we do not include the damage function and we focus on climate policy costs net of environmental benefits.

capacity determines demand of fuels from the power sector: coal, oil, gas, uranium and biomass. Oil is purchased from the international market. The expenditure for fuels other than oil (including biomass) is instead modeled as a sunk cost for the economy.

The major pitfall of WITCH is the low detail in non-electric energy technologies as it lacks a full set of end-use energy technologies and does not distinguish between transport and residential energy uses. Therefore, the demand of biomass from the transportation sector is not included in this analysis.[3] However, this issue is not likely to be of concern in this study since woody biomass is generally not used in the transport sector.

In WITCH, emissions from fossil fuels used in the energy sector and from land use changes that release carbon sequestered in biomass and soils (LULUCF) are endogenous in the model. Emissions of CH_4, N_2O, SLF (short-lived fluorinated gases), LLF (long-lived fluorinated) and SO_2 aerosols, which have a cooling effect on temperature, are also identified. Non-CO_2 gas and aerosol emissions are exogenous in the baseline scenario as are the abatement cost curves for non-CO_2 gas emissions (Bosetti et al. 2011). A climate module governs the accumulation of emissions in the atmosphere and the temperature response to growing GHG concentrations.

Finally, WITCH is calibrated to reproduce the observed value of GDP and other energy variables in 2005. All monetary values are expressed in 2005 USD, using market exchange rates.

2.2. The forestry model

In this analysis, we rely on the dynamic Global Timber Model (GTM) (Sohngen et al. 1999). This model has recently been used to study a woody biomass program in the US (Daigneault et al, 2012).

The forest model contains 200 forest types in 16 regions. The 200 forest types can be aggregated into four broad categories: boreal, temperate hardwood, temperate softwood, and tropical. The intensity of forest management is determined endogenously. Low valued forests are managed lightly with minimal inputs. Moderately valued forests are managed more actively including replanting after harvest. High-value forests are managed as plantations with intensive forest management inputs. Finally, inaccessible forests are left in a natural state unless global timber prices are high enough to justify creating access. The model finds that generally, high valued forests are located in the subtropics, moderate valued forests are in the temperate softwood zone, and low valued forests are in the boreal and tropical forests.

[3] The model was recently expanded to include a transport sector representing the use and profile of light domestic vehicles (LDVs) but this latest version was not used in this study (see Bosetti and Longden, 2012).

The model also captures the age of the timber on each piece of land (and thus resembles a vintage capital model). The stock of timber on the land is determined by a site specific growth function depending on the underlying productivity of land in each region, the type of forest, and management intensity. The supply of timber is consequently also a function of time since it takes time to grow a forest.

The model captures the behavior of a competitive forest industry. Land that is set aside for conservation is taken out of timberland. However, one weakness of the model is that it does not capture segments of the forest sector that are not competitive. The model does not reproduce the fact that governments constrain harvests on public forestland. The model also does not reproduce the fact that there is too much harvest on most common property forests. Although it is clear that both practices are inefficient, it is not clear what net effect these two phenomena have on global timber supply. That is, it is not clear what bias the model has introduced because it assumes the timber market is universally efficient.

In the original GTM model (Sohngen et al., 1999), forestry demand is represented by a single aggregate demand function for industrial wood products[4]. This demand function is assumed to grow over time as the global economy grows:

$$Q_t^{ind} = AZe^{\eta\theta t} P_t^{\omega}, \qquad (1)$$

where A is a constant, Z is income which grows exponentially over time at rate η, θ is income elasticity, P_t is the international price of timber and ω is the price elasticity. Empirical evidence suggests that θ is equal to 0.9, ω is equal to 1.1, and η is equal to 1% (Sohngen et al 1999; Daigneault et al. 2012).

In this paper, we introduce a required amount of woody biomass for energy, Q^{bio}, which is determined by the energy model for each period given the implied price of wood. The amount of biomass requested by WITCH is then fixed in GTM.

The total global demand of wood Q^{tot} in GTM is therefore:

$$Q_t^{tot} = Q_t^{ind}(P_t) + Q^{bio}. \qquad (2)$$

The total wood supply comes from a host of regions that all have forests. We assume there is an international market for timber that leads to a global market clearing price. We further assume that there is also an international market for woody biomass. If woody biomass is going to directly

[4] Industrial wood products are inputs into products like lumber, paper, plywood, and other manufactured wood products.

compete with wood products, competition for supply will equilibrate their price. The timber model solves for the price of biomass given the quantity that is desired.

Following Sohngen et al (1999), the model solves a dynamic problem that equates supply with this aggregate demand. For example, the model chooses the age class (a) to harvest trees in each forest[5]. Hence, the total quantity of timber, Q^{tot}, depends upon each hectare harvested in each age class, *H(a),* and the growth function *V* which is a function of age class and management intensity (m_{t0})[6] such as:

$$Q_t^{tot} = \sum_{a=1}^{A} \left[H_{a,t} V_{a,t} \left(m_{t0} \right) \right]. \qquad (3)$$

The model also chooses management intensity and planting. There are a host of costs for management intensity, additional land, and transportation to markets (Daigneault et al. 2012). In particular, the costs of accessing, harvesting, and transporting timber to markets in accessible and highly valuable plantation forests are assumed to be constant marginal costs. While the costs of accessing new forests at the inaccessible margin are assumed to rise with additional harvests. The costs of planting forests in accessible regions are assumed to be constant for each hectare planted in a given time. Similarly, the costs of replanting existing highly valuable plantation forests are constant but the costs to establish new hectares in inaccessible area are assumed to increase as additional hectares are established. Finally, the costs of establishing new plantations are assumed to be fairly high as new plantations require substantial site preparation efforts to obtain the desired high growth rates.

The final major cost component is the cost of renting land for forestry. The model takes into account the competition of forestland with farmland using a rental supply function for land. So, for example, if timber prices rise relative to farm prices, the model predicts that timber owners will rent suitable farmland for at least a rotation. Similarly, if timber prices fall relatively to farm prices, suitable forest land will be converted back to farmland upon harvest. The total amount of forestland is therefore endogenous.

The model solves assuming there is a social planner maximizing the present value of the difference between consumer surplus and the costs of holding timberland and managing it over time. It is an optimal control problem given the aggregate demand function (which contains the required biomass for energy), starting stock, costs, and growth functions of the model. It endogenously solves for timber prices and the global supply of both woody biomass and industrial timber and optimizes the

[5] Timber shifts from one age class to the next, unless harvests occur.
[6] Management intensity for forests is decided at the time of planting, or t0.

harvest of each age class, management intensity, and the area of forest land at each moment in time. The timber model is forward looking with complete information.

2.3. The soft link

We rely on a soft link between WITCH and GTM. GTM has been soft linked with integrated assessment models before to calculate optimal sequestration programs (Sohngen et al. 2003 and Tavoni et al. 2007). In this study, we soft link WITCH and GTM to study woody biomass. This link was first implemented by Tavoni et al. (2007). However, both models have been modified since this earlier research. First, the option of combining biomass with carbon capture and storage (CCS) has been introduced recently in WITCH. Second, we introduce the demand for biomass in the forestry model.

WITCH calculates global consumption per capita (income) and the quantity of woody biomass demanded in each time period. We then introduce this quantity of biomass in each time period into GTM and determine the price required to supply that global quantity. 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.

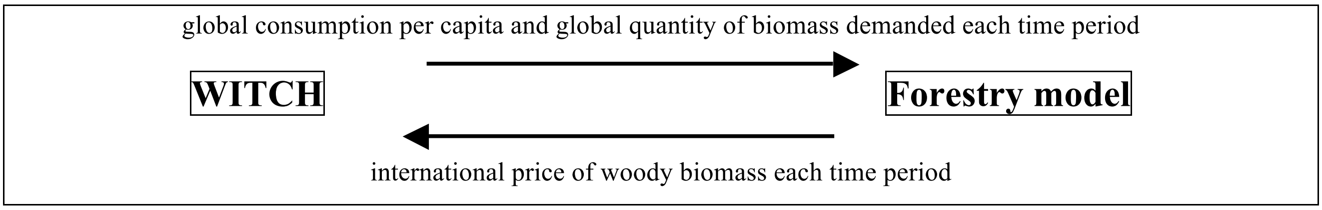


Figure 1 Soft-link of WITCH and GTM

2.4. Details

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. 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.

We assume that only wood can be used to meet the demand of 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 (Daigneault et al. 2012). Also the carbon content of woody biomass is included in WITCH: we assume that on average 1 Twh of bio-energy releases 0.00016 Gt C previously stored during the growth of trees and produces extra sequestration[7] of 0.0001 Gt C in soil, slash and market.

We assume that woody biomass is used only in integrated gasification combined cycle (IGCC) power plants with CCS.[8] 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[9] (Bosetti et al. 2006). 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 (Bosetti et al. 2006).

[7] 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.

[8] 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.

[9] Similar assumptions have been found in the literature, in Luckow et al. (2010) the efficiency of biomass IGCC plant is equal to 41.6% while for Koornneef et al. (2012) is 43-50%. Luckow et al. (2010) assume a CCS capture rate of 91% in 2020, growing to 94% in 2095, Krey and Riahi (2009) assume a capture rate of 90% and Koornneef et al. (2012) a capture rate of 90-95%.

2.5. Scenarios

In this study we use a baseline scenario and three mitigation scenarios. The baseline scenario is a Business As Usual (BAU) scenario with no greenhouse gas mitigation policies over the century. According to WITCH, the average global GDP per capita grows from 6,900 USD in 2005 to 18,000 USD in 2050 and to 39,634 USD in 2100. Global total primary energy supply is 436 EJ/yr in 2005, 820 EJ/yr in 2050 and 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 and therefore radiative forcing equal to 6.6 W/m^2 (Carraro et al. 2012).

We then examine three mitigation scenarios that lead to radiative forcing levels of 3.7, 3.2 and 2.5 W/m^2. The purpose is to show how the demand for biomass would change depending upon the mitigation scenario. The long term objectives correspond to GHG concentrations of 560, 500 and 450 ppm CO_2-eq respectively.

We solve WITCH using a global carbon price as the tool. 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 least cost carbon price would be 4, 7 and 14 USD/tCO_2 in 2015 and would reach 158, 576 and 1161 USD/tCO_2 in 2100 across the three scenarios. We assume no sequestration policies (other than carbon capture and storage) are available in this analysis.

3. Results

3.1. Biomass demand

We assume that using woody biomass for energy is carbon neutral. That is, we assume that the carbon released during combustion was 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). In addition, we assume that biomass power plants receive credits for the extra forest sequestration.[10] 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

[10] This means that, at the time of burning biomass, power plants receive a subsidy equal to the carbon tax for each extra ton of carbon stored in forest with slash and soil.

switch wood into fuel, the carbon price must be about 130 USD/tCO_2. In the most stringent scenario, woody biomass is used as fuel in 2045, in the most moderate scenario in 2055, and in the most moderate policy in 2060.

Because carbon prices rise over time, there is an ever increasing incentive to use woody biomass each decade. It is also true, that as one moves from a mild to a stringent long term mitigation target, the higher price path encourages more cumulative use of woody biomass. Going from the 3.7 to the 2.5 W/m^2 target increases the demand of woody biomass from 8.2 to 15.2 billion m^3/yr (from 77 to 144 EJ/yr) in 2100 (Figure 2). Note, however, that the model is forward looking so that the timber model anticipates the demand for woody biomass far before it is actually burned.. In all scenarios, the biomass consumed is burned in IGCC power plants equipped with CCS which provides 13-26% of global electricity by 2100 depending on the scenario.

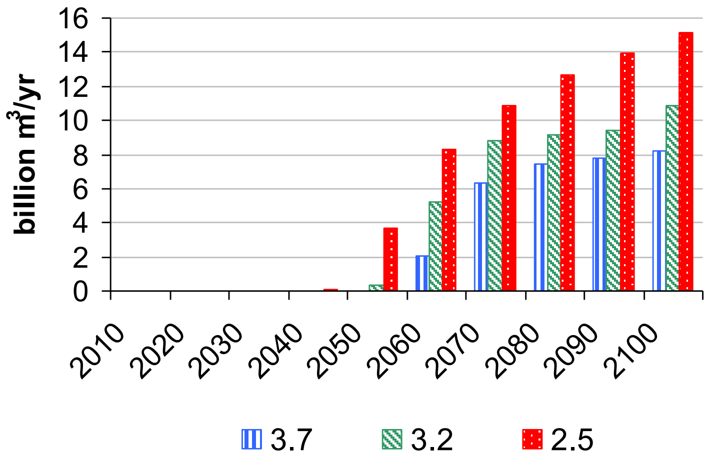


Figure 2 Biomass from forest for energy consumed at the global level 2010-2100 under different mitigation policy scenarios

3.2. Forest sector and timber price

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. By 2100, wood quadruples in price to almost 780 USD/m^3 for the most moderate scenario and it is almost nine times bigger in the most stringent scenario reaching 1650 USD/m^3 (Figure 3).

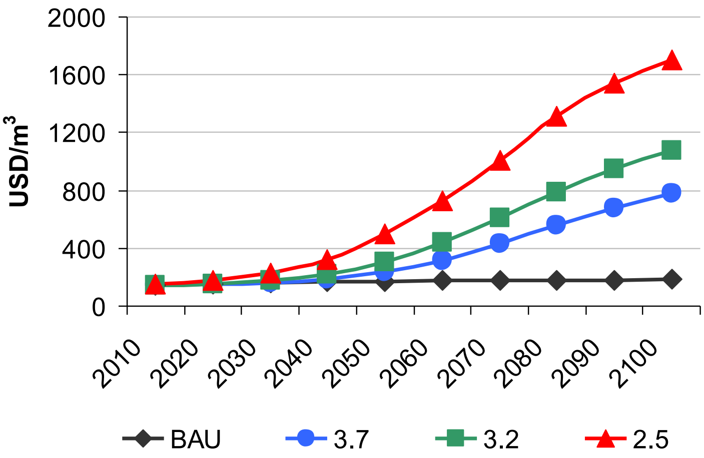


Figure 3 International price of wood under the BAU scenario and climate policy scenarios

These changes in price encourage a large expansion of total timber production in the second half of the century. In the BAU scenario with no additional woody biomass, total global production reaches 3.3 billion m^3/yr by 2100. However, in the most stringent scenario, total global timber production almost quintuples by 2100 to 15.4 billion m^3/yr. Even in the most moderate scenario, total wood production is more than double reaching 8.8 billion m^3/yr by 2100.

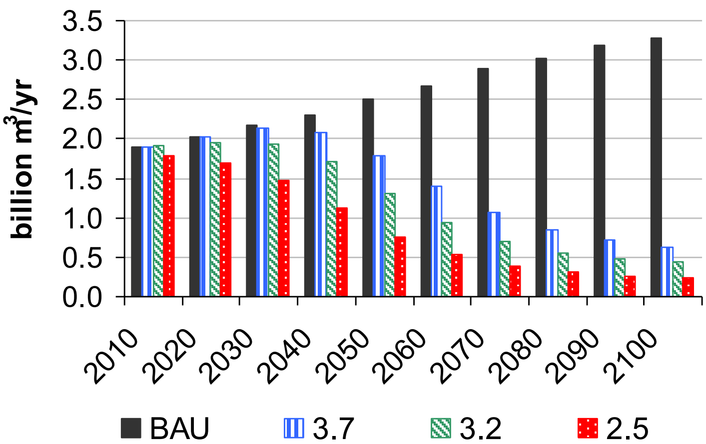


Figure 4 World industrial timber production under the BAU scenario and climate policy scenarios

Despite the huge increase in wood supply, the traditional industrial wood sector (sawtimber and paper) shrinks. In the BAU scenario, rising demand causes the industrial wood sector to grow slowly over time reaching 3.3 billion m^3/yr by 2100. However, by 2100, industrial wood demand falls to 0.2 billion m^3/yr in the most stringent scenario. Even with the least stringent policy, industrial wood quantities fall to 0.6 billion m^3/yr (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 effect from the reduction of global consumption per capita[11]). The most 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 area and carbon sequestration

In order to support the large increase in wood supply, forestland expands dramatically. In the BAU scenario, the global forestland that is harvested remains somewhat constant over the century at 350 million ha. As mitigation increases, this forestland increases both over time and across scenarios (Figure 5). Because the model is forward looking, forestland expands before biomass is actually burned in great quantities. Already by 2060, forestland has expanded by 195−348 million ha depending on the scenario. By 2100, forestland area has expanded by 70% in the most moderate scenario and by 95% in the most severe scenario with respect to the BAU scenario. Because of the inelasticity of inaccessible forests supply in the forestry model, the expansion is mainly into farmland and only partially into inaccessible forests.[12] A by product of the woody biomass program is therefore a decrease in food production and higher prices for food.

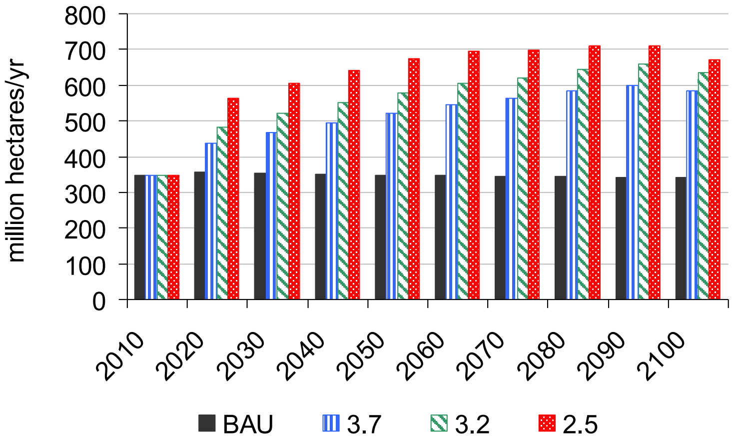


Figure 5 Forest area under the BAU scenario and the three carbon taxes

As the forest area expands, it will capture and store more carbon with respect to the BAU scenario. Figure 6 compares the additional carbon stored in forests each year in each mitigation scenario

[11] The introduction of the carbon tax will reduce the world consumption per capita (Z in Equation 1) by 0.6-2.1% in 2050 and by 2.6-9.7% in 2100 with respect to the baseline scenario.
[12] Inaccessible forests are reduced by 1-2% relative to the baseline scenario.

relative to BAU. In the figure, a negative value implies that the forest is acting as a sink for forest carbon and absorbing carbon. A positive value implies that the forest is acting as a source of emissions. The methodology for carbon accounting in this paper was described by Sohngen and Sedjo (2000) and updated by Daigneault et al. (2012). We assume that the total ecosystem carbon is given by the aboveground forest, slash, and below ground soil carbon.[13] We also track the variation of both carbon stored in timber products (yellow bar) and emissions from fuel used to harvest and transport wood to be processed (orange bar) relative to BAU from the initial period 2010.

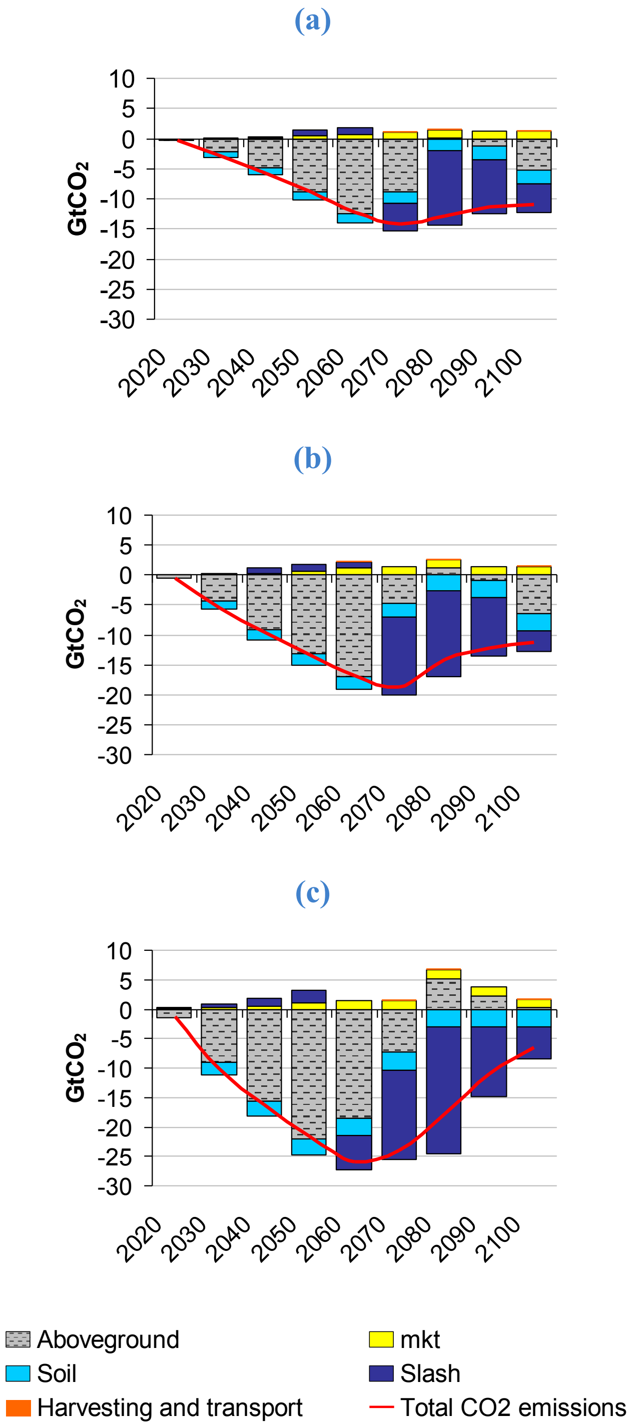
In the BAU scenario, global forests accumulate a small amount of carbon in the first half of the century and then roughly hold that carbon constant for the rest of the century. By 2100 the BAU forests stores an additional 66 Gt CO_2 or about 0.8 Gt CO_2 per year. With the mitigation scenarios, there is a distinct increase in the global stock of carbon stored in forests that increases by 685 Gt CO_2, 908 Gt CO_2 and 1279 Gt CO_2 by 2100 (or about 9.4-16.8 Gt CO_2/yr stored) as the scenarios progress in stringency.

Figure 6 tracks also where in the forest the carbon is accumulating. At first, the accumulation is mostly above ground biomass as trees are grown in preparation for the biomass program. There is also some below ground accumulation of soil carbon as farmland is converted back into forests. In the second half of the century, the forests will be harvested for energy and the aboveground carbon will be burned but then captured by CCS.[14] However, there is a large growth in woody debris left in the woods. Finally, because overall wood products are falling with the mitigation strategies, the amount of carbon stored in market products (which is small) is declining.

Our analysis compares the size of the biomass program to all the mitigation being undertaken in WITCH (Figure 7). Not only is the biomass program a carbon neutral source of energy, but it also reduces the CO_2 in the atmosphere. As the carbon tax rises, the demand for biomass rises, and more CO_2 is sequestered by both the forest (Extra forest sequestration in Figure 7) and the CCS technology (CCS_biomass in Figure 7). Altogether, biomass accounts for 20-27% of total GHG cumulative abatement for 2020-2100. The extra stock of carbon in the forest accounts for 256-574 Gt CO_2 while the extra stock in the ground (from CCS) accounts for 341-647 Gt CO_2. Note that a formal forest sequestration program is not a necessary precondition in order to obtain the forest sequestration gains. The market itself will store this extra stock because of the incentives of the woody biomass program alone. The woody biomass program is consequently a clever mechanism to secure carbon sequestration benefits.

[13] First, above ground carbon accounts for the carbon in all tree components (including roots) as well as carbon in the forest understory and the forest floor. Second, belowground carbon is the carbon left over after timber harvest and removal of carbon in products. Finally, soil carbon is assumed to be constant unless there is land use change.

[14] In this study bio-energy is always combined with the CCS technology. Therefore, 90% of the amount of carbon released is sequestered back through CCS.



Notes: a negative value implies that the forest is acting as a sink for forest carbon and absorbing carbon. A positive value implies that the forest is acting as a source of emissions.

Figure 6 Change in emissions from forest with respect to the BAU scenario in (a) 3.7 W/m^2; (b) 3.2 W/m^2; and (c) 2.5 W/m^2 tax scenarios

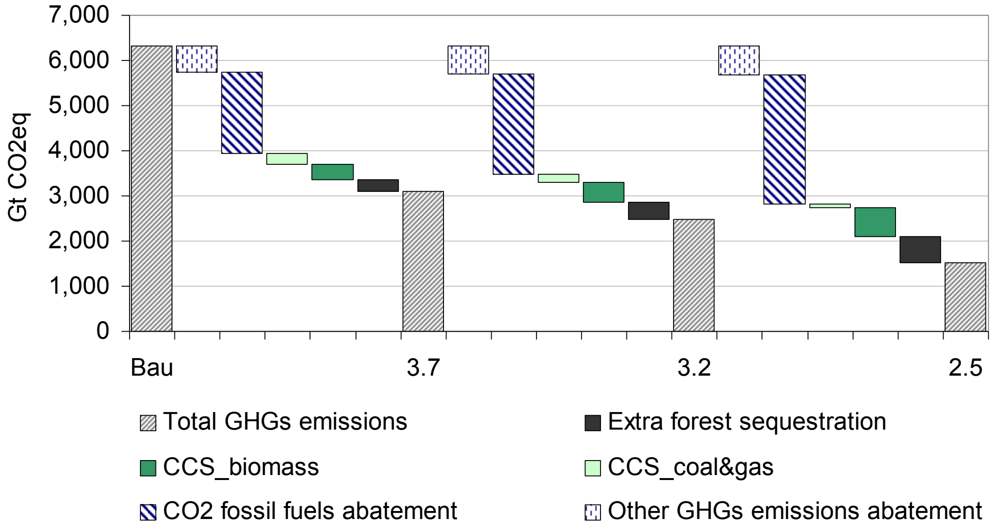


Figure 7 Cumulative GHGs emissions 2020-2100 under the BAU and the three mitigation scenarios

4. Conclusions

The aim of this paper is to provide a global, dynamic and detailed description of the woody biomass supply under climate mitigation scenarios. There are no studies in the literature which combine these three aspects in one analysis on woody biomass. Some are region-specific (Ince et al. 2011; 2012; Moiseyev et al. 2011; Daigneault et al. 2012; Lauri, et al. 2012). Others use a static approach (Raunikar et al. 2010; Buongiorno et al. 2011). A few provide a global and dynamic analysis but they lack a detailed description of the forestry sector (Gillingham et al. 2008; Popp et al. 2011).

Through the soft link of the economic model WITCH (Bosetti et al. 2006; 2007; 2009) and the forestry model GTM (Sohngen et al. 1999; Sohngen and Sedjo 2000; Sohngen and Mendelsohn 2003; Daigneault, et al. 2012) we analyse, in a dynamic framework, the demand for biomass from WITCH along with the supply of biomass from GTM. A BAU scenario is contrasted with three mitigation strategies that would lead to radiative forcing of 3.7 W/m^2, 3.2 W/m^2 and 2.5 W/m^2 in 2100.

We assume that woody biomass energy is carbon neutral. The carbon released during combustion is offset by the carbon captured growing the trees. That is, we ignore the fact that the carbon is captured prior to being released. As carbon taxes rise, they make woody biomass more attractive relative to fossil fuel. Because carbon prices rise over time, there is an ever increasing incentive to use woody biomass each decade. Total timber production expands significantly in the second half of the century.

It is also true, that as one moves from a mild to a stringent long term mitigation target, the higher price path encourages more cumulative use of woody biomass. Going from the 3.7 to the 2.5 W/m^2 target increases the demand of woody biomass from 8.2 to 15.2 billion m^3/yr and the international price of wood from 4 to 9 times by 2100. Despite the huge increase in wood supply, the traditional industrial wood sector (sawtimber and paper) shrinks from 3.3 billion m^3/yr in the BAU to 0.2-0.6 billion m^3/yr in mitigation scenarios by 2100. 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.

In order to support the large increase in wood supply, forestland expands dramatically by 70-95% relative to the BAU. Because of the inelasticity of inaccessible forests supply in the forestry model, the expansion is mainly into farmland and only partially into inaccessible forests. A by product of the woody biomass program is therefore a decrease in food production and higher prices for food. However, there will be some pressure to utilize forests that otherwise would have been left unmanaged.

As the forest area expands, there will be an increase in the global stock of carbon stored in the forest of 685-1,279 $GtCO_2$ by 2100. At first, the accumulation is mostly above ground biomass as trees are grown in preparation for the energy program. There is also some below ground accumulation of soil carbon as farmland is converted back into forests. In the second half of the century, the forests will be harvested for energy and the aboveground carbon will be burned but then captured by CCS. However, there will also be a large growth in woody debris left in the woods. Therefore, an important research question will be whether it is better to leave this debris in the woods or harvest it for bio-energy.

Overall, the biomass program with the CCS technology plays a key contribution to GHG emission reductions in all scenarios providing 20-27% of all mitigation for 2020-2100. The extra stock of carbon in the forest accounts for 256-574 Gt CO_2 while the extra stock from CCS accounts for 341-647 Gt CO_2. Note that a formal forest sequestration program is not a necessary precondition in order to obtain the forest sequestration gains. The market itself will store this extra stock because of the incentives of the woody biomass program alone. The woody biomass program is consequently a clever mechanism to secure carbon sequestration benefits. Second, the results reveal the advantage of using woody biomass rather than crop bio-energy. Crop bio-energy will have exactly the opposite effect on forest carbon sequestration because it would increase the relative value of cropland causing forestland to shrink (Fargione et al. 2008; Melillo et al. 2009; Searchinger et al. 2009; Wise et al. 2009).

Finally, we do not include the impact of climate change on land which might influence the future supply of wood and biomass. This topic is an important issue to be addressed in future research.

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