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Alice Favero, Robert Mendelsohn

Abstract: Although storing more carbon in forests should be part of an efficient mitigation program, it is unclear how to create effective incentives to make this happen. The literature largely has focused on giving landowners direct incentives to store carbon. This paper explores an alternative mechanism to increase forest carbon sequestration by creating a market for wood bioenergy. By raising the value of wood, the program encourages landowners to convert vast amounts of land to forest, which incidentally increases forest carbon. By providing an indirect subsidy on woody biomass, governments can give even more incentive to reward this carbon sequestration.

JEL Codes: Q23, Q42, Q54

Keywords: BECCS, Carbon sequestration, Climate change, Forestry, Integrated assessment model, Mitigation, Woody biomass

THE WORLD FACES A DAUNTING institutional hurdle to create carbon markets to mitigate greenhouse gases. This paper focuses on just one piece of this mitigation effort—storing carbon in forests. Economics studies of mitigation suggest that carbon sequestration in forests is cost effective (Sohngen and Mendelsohn 2003; Stavins and Richards 2005). By reducing deforestation, increasing planting, intensifying forest management, and lengthening rotations, society can store significant amounts of carbon in the world's forests (Sohngen and Sedjo 2000; Sohngen and Mendelsohn 2003; Richards and Stokes 2004; Sathaye and Andrasko 2007). The magnitude of the optimal carbon sequestration program varies with the stringency of the mitigation targets or the "price" of carbon (Sohngen and Mendelsohn 2003).

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Although the direct regulation of carbon in forests is a first best solution, the literature has also identified institutional barriers that must be overcome for forest sequestration to work. First, there is a concern about information or monitoring needs since many forests are remote and forests in general are heterogeneous (Sedjo and Marland 2003). It is not trivial to keep track of billions of hectares of land spread across the planet. It is possible that future mechanisms to monitor forests may reduce the costs, but for the moment these monitoring costs are not at all trivial. Second, there is a concern that piecemeal approaches such as clean development mechanism (CDM) projects would be ineffective because of leakage. There is a strong need for national-level monitoring across all major countries with forestland to limit this effect (Andersson and Richards 2001; Richards and Andersson 2001; Andersson, Evans, and Richards 2009; Plantinga and Richards 2010). Third, unless governments rent all forest carbon from forest owners, there is a serious question about additionality.[1] What is the baseline from which government will pay for additional carbon? Individual contracts would help create private incentives to sequester and address the additionality problem (Mason and Plantinga 2013), but there would still be substantial institutional costs in negotiating these contracts and gathering supporting information.

Rather than directly creating a market for carbon sequestration in forests, this study explores creating a permanent woody biomass program for energy as an alternative mechanism to store more carbon in forests. The woody biomass program (driven by a climate mitigation program) raises the price of wood, creating an incentive to store a vast amount of carbon in forests (the amount depending on the stringency of the mitigation program). Firms and individual forest owners would react to these higher wood prices by voluntarily converting land to forests because it would be profitable.

Even without the forest carbon sequestration benefits, using woody biomass for energy is an important mitigation program in its own right. First, the program generates carbon neutral energy that can substitute for fossil fuels. Second, coupling the bioenergy power plant with carbon capture and storage (CCS) devices does not just prevent new emissions; it actually pumps carbon out of the atmosphere. The biomass program with CCS (BECCS) is consequently a major part of emission strategies that involve strict targets such as holding warming to 2°C (Azar et al. 2006; van Vuuren et al. 2007, 2010; Edenhofer et al. 2010; Rose et al. 2012; Kriegler et al. 2014). The Kriegler et al. (2014) study is perhaps the most compelling because it is a comparison of six Integrated Assessment Models (IAMs), all of which rely on BECCS to reach the target of 2°C by 2100. Even with more modest scenarios, BECCS is eventually cost effective by 2100.

1. Additionality is also a problem for CDM-type policies.

But there is a serious concern whether the world can supply the biomass required for BECCS. The IAMs have sufficient information about emissions and energy programs to know how much BECCS they demand. But they do not have sufficient information about the world's land and forest stocks to know how much biomass can be supplied and at what price.[2]

In this paper we simulate the market for woody biomass with a BECCS program by employing the IAM WITCH (Bosetti et al. 2006, 2007, 2009) to determine demand and the Global Timber Model (GTM; Sohngen, Mendelsohn, and Sedjo 1999; Sohngen and Sedjo 2000; Sohngen and Mendelsohn 2003) to determine supply. We rely on WITCH to determine three price paths to reach different radiative forcing targets for greenhouse gases by 2100. Given this price path, we use WITCH to also determine emissions and efficient mitigation technologies (including BECCS). GTM takes the intertemporal demand for woody biomass from WITCH and predicts the regional forestland, forest stocks, and forest management needed to supply this amount of woody biomass over time. As wood prices relatively increase, the forest model buys new land from agriculture that is suitable for growing forest, increases management intensity, and adjusts harvest schedules of existing stocks. The forest model is forward looking and makes decisions decades in advance to provide future wood supply. Given the price of wood from GTM, WITCH recalibrates the size of the BECCS program. The two models are solved iteratively to determine a price schedule over time that equilibrates supply and demand.

The study reveals that there is sufficient global forest to support a sizable BECCS program. A surprising result of this analysis is that the BECCS program would incidentally cause a substantial increase in forest sequestration. By increasing the demand for wood, forestland and forest stocks become relatively more valuable. The market for wood enhanced by the BECCS program provides an incentive for private forest owners to store more carbon. Forest sequestration is a positive externality of the program. However, to take more advantage of this positive externality, governments could apply an indirect subsidy to woody biomass. By paying each cubic meter of woody biomass a subsidy for the additional carbon storage created, the program could capture some of this benefit. Because this is an indirect subsidy, it is not as efficient as direct regulation; however, it avoids the institutional problems associated with managing the stock of forest carbon directly.

The next section presents the two models, the soft link and the policy scenarios. Section 2 analyzes the results of the two models under alternative mitigation scenarios. Given three different stringency targets, we explore the amount of carbon se-

2. Some IAMs include either a land-use module (e.g., for GCAM, see Edmonds et al. 2013) or biomass supply functions (e.g., for MERGE, see Magne et al. 2010).

questered in forests. Finally, section 3 summarizes the results and raises the policy implications.

1. MODELS, LINKING, AND POLICY

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, Sohngen, and Sedjo 2012) that have been used for this analysis. A more complete description of the WITCH model and the GTM model is in the appendix, available online. We then describe the soft link and the assumptions behind both models. Finally, we introduce the policy scenarios.

1.1. 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 (cost-benefit analysis) or on the optimal responses to climate mitigation policies (cost-effectiveness analysis; Bosetti et al. 2006, 2007, 2009).[3]

WITCH has a game-theoretic structure that allows modeling both cooperative and noncooperative interactions among regions.[4] As in the RICE model (Nordhaus and Yang 1996), the noncooperative solution is the outcome of an open-loop Nash game: 13 world regions interact noncooperatively on fossil fuels, energy R&D, and on learning by doing in renewables. The economy of each region is modeled along the lines of a Ramsey-Cass-Koopmans optimal growth model. For each region a central planner chooses the optimal time paths of the control variables—investments in different capital stocks, in R&D, in energy technologies and consumption of fossil fuels—so as to maximize welfare, defined as the regional present value of log per capita consumption.

One of the advantages of WITCH is that the energy sector is well detailed. The role of specific technologies is simulated. First, the model separates electric and nonelectric uses of energy. Second, firms in the power sector generate electricity using nine different technologies: oil, coal, gas, nuclear, wind, hydropower, coal with CCS, gas with CCS, and biomass with CCS. This kind of detail in the energy sector makes it possible to reasonably portray future energy and technology scenarios and to assess their compatibility with the goal of stabilizing greenhouse gas concentrations. Finally,

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

4. In this work we use the noncooperative solution to build both the baseline and the policy scenarios.

by endogenously modeling fuel prices, as well as the cost of storing the CO_2 captured, it is possible to evaluate the implication of mitigation policies on the energy system and all of its components.

Particularly important in this work is how we model the use of woody biomass for energy. In WITCH, woody biomass is used in integrated gasification combined cycle (IGCC) power plants with CCS (BECCS). The biomass from forest residues (small branches and leaves) is assumed to be left in the forest in this analysis. Although biomass from crops is a viable alternative to woody biomass, using crops for biomass increases the relative price of crops to wood and causes the market to reduce forestland and, therefore, forest carbon. The positive externality of woody biomass is a negative externality with crop biomass (Fargione et al. 2008; Melillo et al. 2009; Searchinger et al. 2009; Wise et al. 2009). Once the implications for carbon sequestration are considered, woody biomass becomes a better fuel than crop biomass for BECCS.

As for all other power generation technologies in WITCH, BECCS electricity generation is governed by a Leontief type production function:

$$EL^{\text{beccs}} = \min\{\beta_{\text{beccs}}Q^{\text{wbio}};\ \sigma_{\text{beccs}}CCS^{\text{wbio}};\ \varsigma_{\text{beccs}}OM^{\text{beccs}};\ \eta_{\text{beccs}}K^{\text{beccs}}\}, \tag{1}$$

where $0 < \beta_{\text{beccs}} < 1$ is the efficiency parameter that determines the amount of biomass (measured in energy units) needed to generate one kilowatt hour (kWh) of BECCS electricity. We assume that 1 cubic meter of woody biomass produces 9.2 gigajoules (GJ) of energy (Daigneault et al. 2012) and the efficiency of biomass power plants is 35% (Bosetti et al. 2006).

Demand for woody biomass is then

$$Q^{\text{wbio}} = \frac{1}{\beta_{\text{beccs}}}EL^{\text{beccs}}. \tag{2}$$

The term CCS^{wbio} is the storage capacity needed to sequester CO_2 from BECCS. The total amount of CO_2 removed and stored depends on the carbon content of woody biomass denoted with ω_{wbio}, and on the capture rate of the power plant,[5] denoted with e: $CCS^{\text{wbio}} = e\omega_{\text{wbio}}Q^{\text{wbio}}$. By using equation (2) it is possible to show that $\sigma_{\text{beccs}} \equiv \beta_{\text{beccs}}/e\omega_{\text{wbio}}Q^{\text{wbio}}$. Operation and maintenance costs (OM^{beccs}) are needed to run power plants, and their demand is regulated by ς_{beccs}.

Finally, K^{beccs} measures BECCS generation capacity in power units. The term η_{beccs} is an efficiency parameter that regulates the number of hours of operation of BECCS power plants. Power generation capacity grows as follows:

5. We assume that on average 1 m^3 of woody biomass contained 0.41 tons of carbon and the efficiency of the CCS is 90%.

$$K_{t+1}^{\text{beccs}} = (1-\delta)K_t^{\text{beccs}} + \frac{I_t^{\text{beccs}}}{\phi_{\text{beccs}}}, \tag{3}$$

where I^{beccs} is the investments in BECCS, δ is the depreciation rate of power plants, and ϕ_{beccs} is the investment cost of BECCS generation capacity.

By denoting the interest rate of the economy with r, the cost of generating one unit of electricity with BECCS is thus equal to

$$C(EL^{\text{beccs}}) = \left[\frac{1}{\beta_{\text{beccs}}}P^{\text{wbio}} + \frac{1}{\sigma_{\text{beccs}}}C_{\text{CCS}}(TCCS^{\text{wbio}}) + \frac{1}{\varsigma_{\text{beccs}}} + \frac{1}{\eta_{\text{beccs}}}(r+\delta)\phi_{\text{beccs}}\right], \tag{4}$$

where P_{wbio} is the market clearing price of woody biomass given by GTM through the soft link with WITCH and C_{CCS} is the cost of CCS which is region specific and depends on cumulative storage ($\text{TCCS}^{\text{wbio}}$).

Under a climate policy scenario (in this case a carbon tax) woody biomass will be exempted from paying the carbon price (T) since we assume that the trees capture the carbon that is released during biomass combustion.[6] In addition, since the biomass power plants are equipped with the CCS technology they receive a subsidy for each ton of CO_2 captured and sequestered with the CCS (given by $e\omega_{\text{wbio}}$). Finally, the timber model GTM reveals that a substantial amount of additional forest is required to supply woody biomass needed by BECCS. This much larger forest stores a substantial amount of carbon above ground, in slash, and in the soil. We define this extra sequestration as the difference between the amount of carbon stored in the forest in the baseline scenario (where the demand of woody biomass is equal to zero) versus the carbon stored in the policy scenario.

In this analysis, we are assuming that there is no carbon sequestration program in forests. If a carbon sequestration program was in place, it would reward owners for storing the extra carbon in forests. In the absence of a carbon sequestration program, we are imagining a subsidy on wood that reflects the additional forest in place with the woody biomass program. Since the forest is grown in anticipation of harvests for the woody biomass program, it should be relatively straightforward to detect the increase in global forestland. The wood subsidy is an indirect subsidy, similar to a Pigovian subsidy (tax) on output with a positive (negative) externality. In order to capture this positive externality in WITCH we add the parameter α_{wbio}. The parameter is the average extra sequestration for each cubic meter of wood used for BECCS.[7] We assume that the average value of this subsidy is the added value of the carbon stored in

6. This assumption of bioenergy carbon neutrality has been challenged (see Sedjo 2011).

7. Several test runs of the coupled models have shown that on average 1 m^3 of woody biomass used in the BECCS power plants will increase the stock of forest carbon with

the additional forest in place with the woody biomass program. BECCS power plants would receive a subsidy equal to the carbon price (T) for each extra ton of carbon sequestered using woody biomass. Under a carbon price scenario, the cost of generating one unit of electricity with BECCS is obtained by modifying equation (4) as follows:

$$C(EL^{beccs}) = \left[\frac{1}{\beta_{beccs}}P^{wbio} + \frac{1}{\sigma_{beccs}}C_{CCS}(TCCS^{wbio}) + \frac{1}{\varsigma_{beccs}} + \frac{1}{\eta_{beccs}}(r+\delta)\phi_{beccs} - \left(\frac{e\omega_{wbio} + \alpha_{wbio}}{\beta_{beccs}}\right)T\right]. \tag{5}$$

Finally, the major pitfall of WITCH is the low detail of the 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 for biomass from the transportation sector is not included in this analysis.[8] However, this issue is not likely to be of concern in this study since woody biomass is generally not used in the transport sector.

The model also does not depict the traditional use of biomass for charcoal, heat, and cooking. We consequently may underestimate the supply of woody biomass since bioenergy demand will likely divert timber from these low-valued uses. However, we do not believe that this will have a major effect on the analysis. By the end of the century when BECCS is employed, far fewer households will be relying on charcoal and wood burning for energy. Further, the model does not utilize low-productivity forests for BECCS, so household use of forests for energy is largely independent of BECCS.

1.2. The Forestry Model

The Global Timber Model (GTM) was developed to study dynamic forest markets and policies (Sohngen et al. 1999). GTM is a daughter of a global equilibrium forest model (Sedjo and Lyon 1990) and a dynamic forest model (Sohngen and Mendelsohn 1998). GTM 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. Moderate-valued forests are managed more actively including replanting after harvest.

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respect to the baseline scenario by 0.29 tons. Therefore, we assume that the parameter α_{wbio} is equal to 0.29.

8. A new version of the model includes a transport sector representing the use and profile of light domestic vehicles (LDVs; see Bosetti and Longden 2013).

High-valued 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.

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 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. This weakness of the model is not expected to dramatically alter the results because the model does not depend on all forests but rather just the more productive accessible forests. At least in the current analysis, inaccessible forests are assumed to be left largely unaffected.

In the GTM model (Sohngen et al. 1999), wood demand is represented by a single aggregate demand function for wood which is an input to industrial wood products like lumber, paper, and plywood. This demand function is assumed to grow over time as the global economy grows:

$$Q_t^{\text{ind}} = AZe^{\phi\eta t}P_{\text{wbio},t}^{\omega}, \tag{6}$$

where A is a constant, Z is income that grows exponentially over time at rate η, ϕ is the income elasticity, P_{wbio} is the international price of timber, and ω is the price elasticity. Empirical evidence suggests that ϕ 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^{wbio}, which is determined by WITCH for each period given the implied price of wood and the price of carbon.

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

$$Q_t^{\text{tot}} = Q_t^{\text{ind}}(P_{\text{wbio},t}) + Q^{\text{wbio}}. \tag{7}$$

The total wood supply comes from the regions across the world that have forests. We assume that 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 since (under mitigation scenarios) future prices of wood for biomass will be high enough to make trade affordable. If woody biomass is going to directly compete with wood products, competition for supply will equilibrate their price.

Following Sohngen et al. (1999), the model solves a dynamic problem that equates supply with this aggregate demand. The model solves the problem assuming that 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 harvest of each age class, management intensity, and the area of forestland at each moment in time. The timber model is forward looking with complete information. This dynamic model also implies that rotation lengths are set endogenously as economic conditions change.

Finally, the forest carbon analysis used in this study 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, forest products, and soil carbon. Aboveground carbon accounts for the carbon in all tree components (including roots) as well as carbon in the forest understory and the forest floor. Slash carbon is the carbon left over after timber harvest and removal of carbon in products. Therefore, annual additions to the slash carbon pool depend upon each hectare harvested in each age class, the growth function, and the aboveground carbon. Carbon in timber harvests is estimated by tracking forest products (for the industrial sector) over time. Finally, soil carbon is assumed to be constant unless there is land use change. For instance, when land use change occurs (from forestland to farmland and vice versa), we track net carbon gains or losses over time.

1.3. The Soft Link

In this analysis 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 and Mendelsohn 2003; Tavoni, Sohngen, and Bosetti 2007). In particular, the soft link between WITCH and GTM 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 has been introduced recently in WITCH. Second, we introduce the demand for biomass in the forestry model.[9]

9. A previous version of GTM included only a US woody biomass program (see Daigneault et al. 2012).

In this soft link, WITCH calculates a price path for carbon in order to reach different radiative forcing targets by 2100. We explore a range of radiative forcing targets to understand how the stringency of the concentration targets affects the demand for BECCS. Each carbon path is consistent with (i) the path of global consumption per capita (Z in eq. [6]), which is used to drive the demand for industrial timber products (Q^{ind}), and (ii) the quantity of woody biomass demanded in each time period under climate mitigation scenarios (Q^{wbio}). Both inputs are introduced into GTM, which determines the intertemporal price of wood required to supply the demanded global quantity of wood. This price is then reintroduced to WITCH, which solves for a new quantity of woody biomass demanded.[10] Again, the new quantities are introduced back into the forestry model. The two models iterate back and forth until demand for wood equals supply at the global scale. 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.

For each mitigation strategy, WITCH takes into account the 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.

1.4. Policy

In this study we use a baseline scenario (BAU scenario) which leads to a level of greenhouse gas (GHG) concentration in the atmosphere of 951 parts per million (ppm) and radiative forcing equal to 6.6 W/m^2 (watts per square meter) in 2100 (Carraro, Favero, and Massetti 2012). We then assume that all world regions credibly agree on a uniform global tax $T(t)$ to reduce all GHG emissions from 2015. Taxes are equal to 4, 7, and 14 US$ per ton of CO_2 in 2015 and reach 367, 576, and 1,161 US $/t$CO_2$ in 2100, respectively.[11] These carbon price paths lead to radiative forcing

10. WITCH has 5-year time steps and the forestry model has 10-year time steps. To link the two models, we average the 10-year biomass price steps from GTM to yield 5-year price steps for WITCH.

11. Similar carbon tax paths have been used in Carraro et al. (2012) and Favero and Massetti (2013). The model has been first solved using a cap-and-trade policy tool with borrowing and banking with a 460 ppm CO_2-eq target in 2100. With both when and where flexibility, the optimal level and growth rate of the carbon price have been found. The growth

levels of 3.7, 3.2, and 2.5 W/m^2 (fig. 1). We label the three scenarios according their radiative levels. These policies correspond to long-term GHG concentrations of 560, 500, and 450 ppm CO_2-eq (carbon dioxide equivalent), respectively, and would lead to average increases in temperature of 2.6°C, 2.3°C, and 2.0°C relative to preindustrial levels. Finally, we assume that no sequestration policies (other than CCS) are available.

2. RESULTS

A greenhouse gas mitigation program (a carbon tax or equivalent cap-and-trade program) would credit BECCS for three services. First, biomass provides carbon neutral electricity. Second, the CCS extracts carbon from the atmosphere and permanently stores the carbon below ground. Third, the larger forest stores more carbon in the biosphere. This last service is valued with an indirect subsidy on woody biomass.

With the BAU scenario, carbon prices are effectively zero, and all of these services have no value. In the BAU, there is minimal use of woody biomass for energy (only wood residues at mills would be used). In order for power companies to switch wood into fuel, the carbon price must be about 125 US$/t$CO_2$.[12] It is only when prices reach this minimum level that woody biomass is used as fuel. This happens in 2045 in the most stringent scenario and in 2060 in the most moderate policy examined in this paper. As carbon prices rise over time, the incentive to use biomass increases and the program grows in size. The higher prices associated with more stringent scenarios also lead to a larger woody biomass program. 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 cubic meters per year (from 77 to 144 exajoule per year) in 2100.[13]

In order to supply the additional wood, forestland expands both over time and across scenarios. Because the forestry model is forward looking, forestland expands before the biomass is actually burned. Already by 2060, forestland has expanded by 1,950–3,480 million hectares depending on the scenario. By 2100, forestland area

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rate of the carbon price is then used to determine the three tax trajectories starting from the three representative carbon tax levels in 2015.

12. While a formal forest sequestration could begin at very low carbon prices (Stavins and Richards 2005), the BECCS option would come into play only if the price path reached high levels. However, even in the BECCS program the forest sequestration begins about 50 years before the price reaches high levels since forest owners start investing in forests to serve this new purpose. So that would happen immediately for an aggressive program and by 2050 for a modest program.

13. Although this analysis focuses on the time period 2020–2100, we assume that the climate policy will continue beyond 2100.

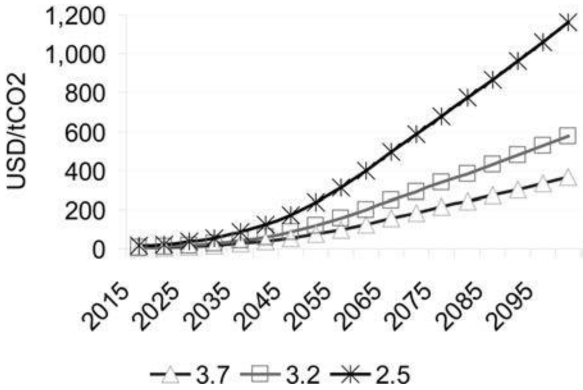

Figure 1. Carbon price scenarios

has expanded by 70% in the most moderate scenario and by 95% in the most severe scenario with respect to the BAU scenario. Most of this land comes from cropland so that there are consequences of the woody biomass program to the supply of food.[14]

As the forest area expands, it will capture and store more carbon with respect to the BAU scenario. Figure 2 compares the carbon stored in forests each year in the BAU scenario and in each mitigation scenario. In the BAU scenario, 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 forest stores an additional 66 gigaton (Gt) CO_2 or about 0.8 Gt CO_2 per year. With the mitigation scenarios, there is instead a distinct increase in the global stock of carbon stored in forests almost immediately. This quick response is caused by the forward-looking timber model recognizing that it must plant trees in advance to supply the future demand for wood. Depending on the stringency of the global mitigation program, cumulative carbon sequestration grows by 685 Gt CO_2, 908 Gt CO_2, and 1,279 Gt CO_2 by 2100 (or about 8.6 to 16.0 Gt CO_2/yr stored).

Figure 3 tracks where in the forest the additional carbon is stored relative to the BAU. The additional carbon is stored in the forest ecosystem in the form of above-ground forest, slash, and soil carbon. However, a small amount of carbon is also lost because there is less carbon stored in timber products (gray bar) and there are

14. Because of the inelasticity of inaccessible forests supply in GTM, forest expansion is mainly into farmland and only partially into inaccessible forests (see Favero and Mendelsohn 2013). Since the land that the model is expecting to use for BECCS is currently in either industrial roundwood or agriculture (where private property rights are largely secure), we do not deal with the issue of security rights.

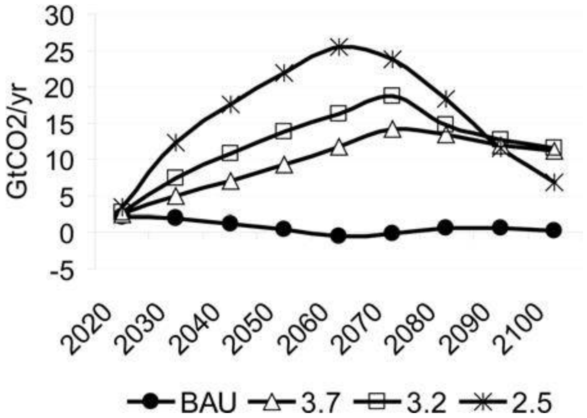

Figure 2. CO_2 stored in forests each year in the BAU scenario and in each mitigation scenario

more emissions from fuel used to harvest and transport wood products, especially biomass.

In the first several decades, most of the accumulation is in aboveground biomass as new forests are created in preparation for the biomass energy program. There is also some belowground accumulation of soil carbon as farmland is converted back into forests. In the second half of the century, the additional sequestration is caused by the accumulation of slash above ground which is a by-product of harvesting.

Figure 4 shows GHG emissions abatement under policy scenarios as the reduction in emissions relative to the BAU. The BECCS program contributes to the overall global mitigation program through three abatement options. First, BECCS contributes to fossil fuel emissions reduction providing approximately 13%–23% of electricity in the second half of the century. Second, the CCS component of CCS keeps pumping more and more carbon out of the atmosphere, storing it belowground (CCS storage in fig. 4). Finally, the extra forest sequestration increases the carbon stored in the biosphere (forest carbon storage in fig. 4). Note that the forest carbon sequestration is the largest component of the BECCS program. All abatement activities not related to BECCS are combined into an "other abatement" category, which includes removing fossil fuels emissions with carbon neutral energy sources other than bioenergy, other-GHGs emissions abatement, and emissions captured and stored in coal and gas power plants.

Figure 4 also shows when the BECCS abatement will happen across time. The benefits of the "carbon neutral" bioenergy and the CCS storage happen in the second half of the century when the biomass is burned. The forest carbon stored in slash also comes in the second half of the century as it accumulates when the trees are harvested. However, the forest sequestration benefit from the increase in aboveground

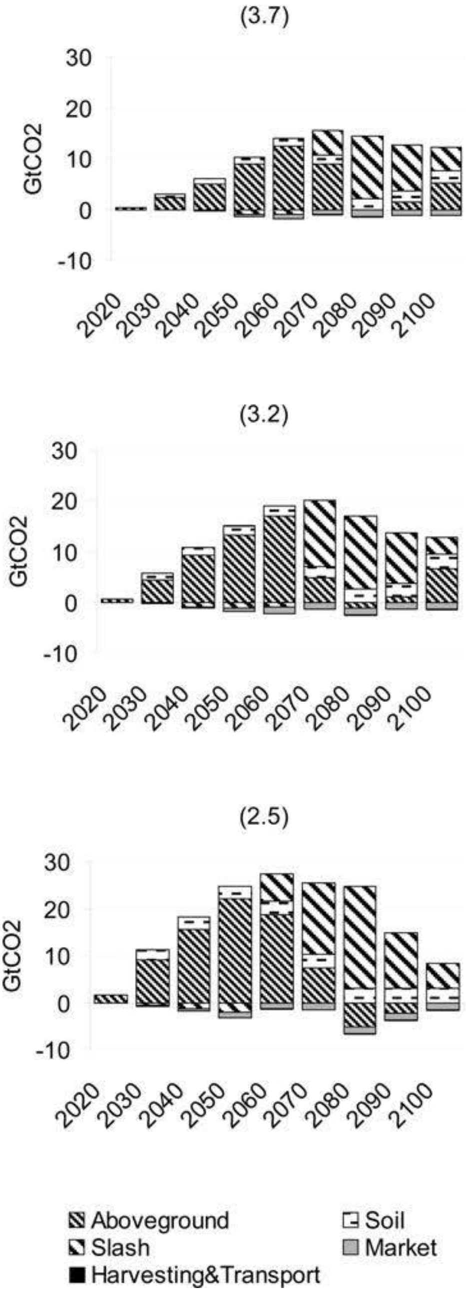

Figure 3. Additional forest carbon sequestration by BECCS over time for three carbon price scenarios. A negative value implies an increase in emissions.

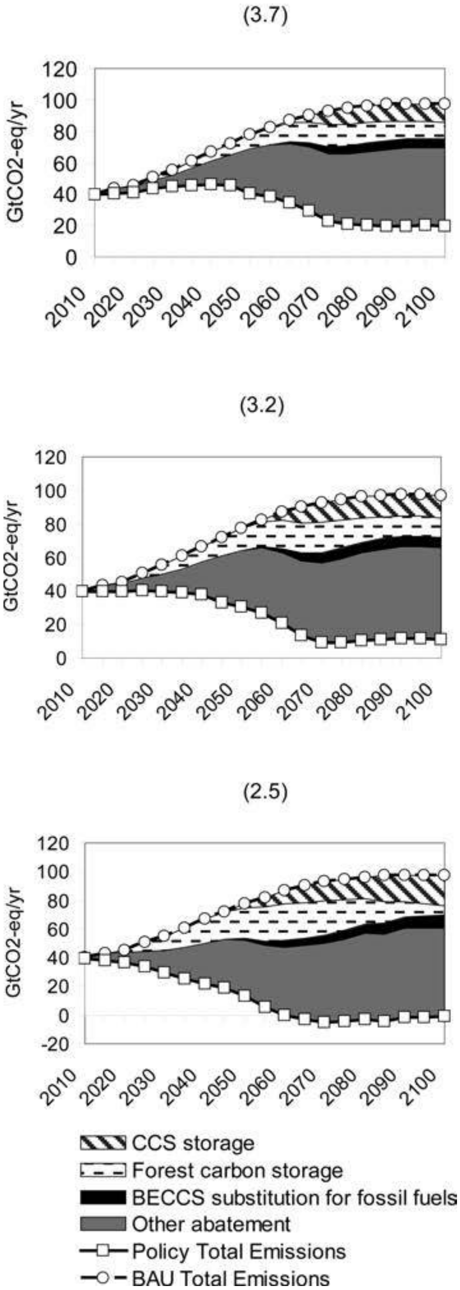

Figure 4. Annual GHG abatement under the three tax scenarios

biomass begins in the first half of the century as trees are grown explicitly to be burned in BECCS. The forest carbon storage from this larger forest remains as long as BECCS continues to be used because a larger forest is needed to sustain the supply of wood for the BECCS program.

Figure 5 displays the cumulative contribution of each major mitigation effort related to BECCS. Between 2020 and 2100, the BECCS program is responsible for removing 1,207–2,214 Gt CO_2. The BECCS program is responsible for 33% – 41% of the total GHG cumulative abatement. The reliance on the BECCS program increases slightly, the more stringent the abatement target. The substitution of wood burning for fossil fuels is responsible for 181 to 288 Gt CO_2 of the BECCS benefit (13%–15%). The storage of carbon deep underground through CCS is responsible for about 341–647 Gt CO_2 (28%–29%). The storage of carbon in the forest is responsible for the remaining 685–1,279 Gt CO_2 (57%–58%). The forest sequestration benefit is consequently the largest component of the BECCS program.

These results show that a global land-use regulatory program (such as reducing emissions from deforestation and forest degradation [REDD]) is not the only way to encourage forest sequestration. The market itself will permanently store this extra stock with a permanent woody biomass program. The woody biomass program is a clever alternative mechanism to secure carbon sequestration benefits.

3. CONCLUSIONS

Forest sequestration can store substantial quantities of CO_2 in live biomass, dead organic matter, and soil pools (Sohngen and Sedjo 2000; Sathaye et al. 2006). Further, forest sequestration is cost effective compared to other mitigation alternatives (Sohngen and Mendelsohn 2003; Richards and Stokes 2004). Yet despite this potential, it is very difficult to design a global regulatory program to realize forest carbon sequestration. Forest sequestration requires extensive monitoring efforts across most of the world forests to be effective, and the cost of monitoring alone may make the program cost ineffective.[15]

This paper explores an alternative mechanism to encourage forest sequestration. The paper finds that woody bioenergy creates a market incentive for forest owners to increase forest sequestration. The mitigation policy dramatically increases the demand for wood for energy. The woody biomass program raises the price for wood, making forests more economically valuable relative to other land uses. Landowners respond by increasing forestland and by increasing the stock of forest on forestland. Increased carbon sequestration is, therefore, a positive externality of the woody biomass program.

15. BECCS would also require monitoring. However, it very likely that carbon storage and biomass power plants would be large-scale industrial sites where monitoring costs would be modest comparing to monitoring each landowner for sequestration.

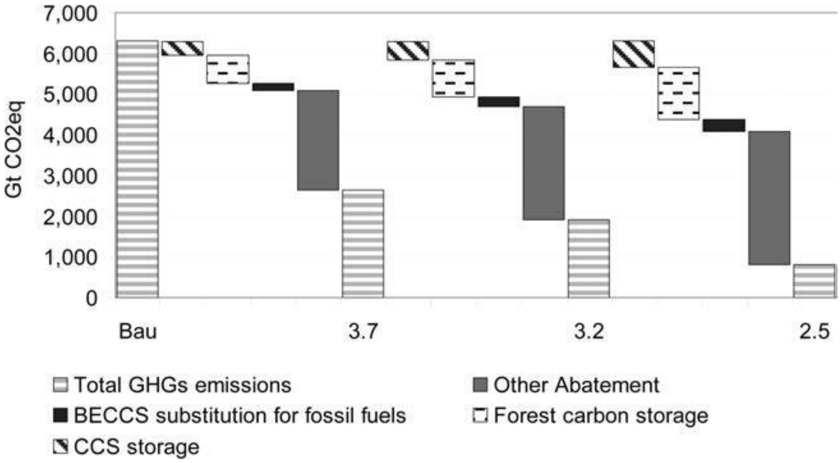

Figure 5. Cumulative GHG abatement under the three tax scenarios

The paper quantifies the positive effect of woody biomass by using two simulation models: WITCH and GTM. WITCH is used to determine the demand for BECCS relative to other mitigation programs over time. Specifically, we rely on WITCH to evaluate three different carbon prices (from modest to severe) to determine the optimal combination of mitigation technologies that are needed over time. This determines the demand for BECCS given the price of wood. GTM is used to determine the supply of wood that can be delivered to BECCS for any specific set of market prices over time. By solving these two models iteratively, one can determine the price schedule that equilibrates the global supply and demand for wood.

Our analysis shows that an extensive woody biomass program is technically feasible and efficient with sufficiently high carbon prices. A limitation of this approach is that burning woody biomass for fuel would only be done if the price of CO_2 exceeds 125 US$/t$CO_2$. In general, that means BECCS would only be employed in the second half of this century. However, the forest sequestration associated with this program would start 40–50 years before BECCS is implemented in anticipation of the higher demand (and therefore price) for wood. Given the set of carbon targets considered in this paper, carbon sequestration would therefore start in the first half of this century. The extent of its use would depend on the stringency of the mitigation target (the price path of carbon).

The study suggests that a woody biomass program would eventually become large enough that a substantial amount of land would be converted back from agriculture to forests. The model predicts that new forestland will come from current farmland and that inaccessible forests are likely to remain as they are. However, the high prices of wood will place ever greater pressure on deforesting land put aside for conservation, especially in tropical countries with weak government enforcement. In the case that land is used for BECCS from places with poorly defined property rights, securing these property rights will be an important prerequisite for sustainability.

A large woody biomass BECCS program would require a substantial increase in the stock of forests and forestland. If coupled with an indirect subsidy on forest fuel to capture the carbon sequestration benefit, the carbon stored in global forests would increase by 685–1,279 Gt CO_2 by 2100. Another 341–647 Gt CO_2 would be sequestered underground through CCS. These extra benefits would of course be conditional on CCS working effectively. Commercial scale extraction has yet to be demonstrated, and the long-term success of storage sites is still unproven. Taking into account that the use of BECCS also reduces CO_2 emissions from fossil fuels by 6%–14%, the woody biomass program would cumulatively account for 1,207–2,214 Gt CO_2 this century. BECCS using woody biomass would account for 33%–41% of total GHG cumulative abatement from 2020 to 2100. One-half of the benefits are from the positive externality associated with forest carbon sequestration.

The elegance of the woody biomass program is that it harnesses markets to encourage local landowners to plant and manage trees, raising the global price of timber and creating market incentives to store carbon. In this way, landowners would voluntarily convert land to forests and store more carbon in forests. A costly program to regulate the carbon actually stored in each forest is not necessary to encourage forest sequestration.

It is useful to contrast the BECCS program with a conservation program such as REDD that creates a permanent aboveground carbon stock in forests. From a carbon perspective, both efforts lead to forest sequestration, a transfer of carbon from the atmosphere to the biosphere. However, BECCS effectively doubles this benefit by continuously adding carbon belowground through CCS and providing energy that substitutes for fossil fuels. In contrast, REDD protects old growth (mature) forest habitat that BECCS would not. With a BECCS program, it is even more important that governments protect forestland whose primary purpose is conservation. This tension between conservation policies and woody (or crop) bioenergy demand needs to be explored further.

It is also useful to review our assumption that woody biomass should be used instead of crop biomass. Both crop and wood fueled BECCS programs create an externality with respect to forest sequestration. With woody biomass, the externality is positive, as the program encourages more carbon to be stored in forests. With crop biomass, the externality is negative, as the higher price of crops encourages landowners to switch from forests to crops (Fargione et al. 2008; Melillo et al. 2009; Searchinger et al. 2009; Wise et al. 2009). Given the critical importance of carbon sequestration in forests, it would appear that the woody biomass program is strongly preferred to a crop biomass program. However, a definitive study comparing both options has not yet been completed.

This study relies on an indirect subsidy of woody biomass for BECCS to partially capture the benefit of carbon sequestration. Direct regulation of forest carbon could address these externalities more efficiently by placing a price on forest carbon. An important topic that has not yet been explored is the interaction between a woody biomass BECCS program and a direct forest sequestration program. It would be interesting to explore how the woody biomass program would affect forest sequestration in a first best world.

Finally, an important assumption in this analysis is that governments would provide convincing evidence in advance that they would employ BECCS when it became cost effective. This is equivalent to governments committing in advance to a carbon price schedule or to a declining cap in a cap-and-trade program. Without this assurance, the forest sector would likely be unwilling to make the substantial investment in forests in time to support a large BECCS program in the second half of the century. Of course, this problem of future commitment is not unique to BECCS and applies to most mitigation efforts as well as forest sequestration offsets.

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