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Carbon Storage and Bioenergy: Using Forests for Climate Mitigation

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Keywords: Climate Change, Woody Biomass, Carbon Sequestration, BECCS, Forestry, Carbon Mitigation, Integrated Assessment Model

JEL Classification: Q23, Q42, Q54

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Abstract
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1. Introduction

In most of the studies surveyed by Working Group III of the IPCC Fifth Assessment Report (AR5), large scale afforestation and bioenergy combined with carbon capture and storage (BECCS) were utilized as carbon dioxide removal (CDR) options to meet low stabilization targets (see Figure 6.35, Clarke et al. 2014). These studies rely on either crop residues, crop biomass, or forests for feedstock (Creutzig et al. 2104). Unfortunately, there is a limited amount of crop residues, they are currently used to fertilize fields, and they are expensive to collect. The crop bioenergy studies often assume that bioenergy could be produced on marginal and degraded land and so would have limited land use effects. However, the low productivity of marginal lands also limits the net energy that can be produced. Most bioenergy crops are currently grown on high productivity land. In this case, heavy reliance on crop bioenergy will dramatically increase the demand for cropland putting global pressure to convert forests into cropland (Searchinger et al.2008; Delucchi, 2010; Hertel et al. 2010). The resulting loss of carbon stored in forests would substantially reduce the merits of using crops as fuel for BECCS.

If BECCS cannot rely on cropland for carbon mitigation, can forestland be used instead? What is the best way to use forestland for carbon mitigation? Studies have previously suggested that forests can be an effective tool to store more carbon (Stavins, 1999; Plantinga, Mauldin and Miller 1999; Sohngen and Mendelsohn 2003; Sathaye and Andrasko 2007). In the United States, Richards and Stokes (2004) showed that carbon prices from 1-41 $\$/tCO_2$ could generate an increase in total forest carbon of 0.5-2.7 $GtCO_2$. In 2030, the studies surveyed by the IPCC AR5 estimate potential carbon sequestration for global afforestation and reforestation activities of 7.18-10.60 $GtCO_2eq/yr$ for carbon prices up to 100 $\$/tCO_2$ (Smith et al. 2014). Using integrated assessment models (IAMs) Sohngen and Mendelsohn (2003) show that carbon sequestration in forests is cost effective at low carbon prices. Tavoni, Sohngen and Bosetti (2007) show that carbon sequestration in forests is also cost effective for aggressive climate targets. Sequestering carbon in forests represents a significant near-term and inexpensive mitigation option.

Previous studies have shown that using forests to fuel bioenergy combined with CCS technology (BECCS) is also an attractive mitigation option at least for aggressive carbon targets. The carbon dioxide fixed in woody biomass is captured when the biomass is burned and then sequestered in underground deposits (Obersteiner et al. 2001; Rhodes and Keith 2005; 2008; Azar et al. 2006; 2010; Chum et al. 2011). BECCS delivers two desired outputs: it generates electricity and it lowers the stock of CO_2 in the atmosphere. Many IAMs need BECCS to reach stringent stabilization targets. BECCS allows the world to overshoot target concentrations and still reach them in the long run by providing a mechanism to extract CO_2 from the atmosphere. BECCS is cost effective because it delays other costly mitigation measures until the second half of the century (Krey and Riahi 2009; van Vuuren et al. 2010; Thomson et al. 2011; Azar et al. 2006; Edenhofer et al. 2010; Rose et al. 2012; Blanford et al. 2014; Edmonds et al. 2013). Many IAMs assume large-scale bioenergy usage by the end of the century, with a wide range of estimates on the future bioenergy demand from 70 to 400 EJ/yr by 2100 (Azar et al. 2006; 2010; van Vuuren et al. 2007; 2013; Popp et al. 2011; 2014; Calvin et al. 2009; Gillingham et al. 2008; Luckow et al. 2010; Klein et al. 2013; Rose et al. 2012; 2014). Furthermore, they tend to agree that a price of $100 per ton of CO_2 is needed to use BECCS in most scenarios (Krey and Riahi, 2009; Azar et al. 2010; Luckow et al. 2010; Edmonds et al. 2013). The mitigation potential of this technology is large: removing about 3-10 $GtCO_2/yr$ by 2050 (Clarke et al. 2014). Finally, although many studies assume that crops are used for BECCS, using wood as a feedstock for BECCS creates a positive externality to increase carbon storage in forests (Favero and Mendelsohn 2014).

Clearly forests can be used to sequester carbon from the atmosphere in living biomass, and forests can also be used as a feedstock for BECCS, but it is not well understood how these two options may interact over time. Some management actions that enhance the stock of carbon in forested ecosystems, such as preserving natural areas, could increase costs for producing biomass for energy production. The choice of whether to regenerate the same type of forest that was harvested, or whether to regenerate fast-growing plantation types likely will depend on the intended use of the forest, carbon sequestration or biofuels. No study to date has examined how incentives for forest carbon sequestration and BECCS will affect land use and forest management.

The paper considers both potential policies by combining a global model of forests, GTM (Sohngen et al. 1999; Sohngen and Mendelsohn 2003), with the Integrated assessment model WITCH (Bosetti, Massetti and Tavoni 2007; Bosetti et al. 2006; 2009). The soft-link of the two models allows us to incorporate the demand for bioenergy from the WITCH model with the supply of wood for fuel from GTM. WITCH takes into account the demand for carbon storage and bioenergy in competition with other mitigation options. GTM reflects the supply for wood. The model captures not only adjustments in land use but also how forest management responds to timber and carbon prices. Other IAMs ignore forest management and thus cannot capture the important carbon changes associated with forest management. Which forests would be managed versus natural? How long would rotations be under different incentives? What would happen to management intensity in managed forests?

This paper makes three important contributions. First, the paper compares the effectiveness of just using forests for carbon sequestration (SEQU) versus just using forests for BECCS. Second, the paper reveals it is better to use BECCS+SEQU than either BECCS alone or SEQU alone. Third, the paper shows how all three forest CDR programs affect overall carbon mitigation, forestland, natural forest, and cropland. Forest carbon mitigation technologies can contribute up to one fourth of total mitigation. They substantially increase forestland at the expense of cropland. With just SEQU, they also increase the amount of natural forest. However, with BECCS, they tend to decrease natural forestland in the long run.

The paper is organized as follows. Section 2 describes the models and methods used for the analysis. In Section 3, we discuss the results of the two models under different CDR options. Finally, Section 4 summarizes the results and discusses the policy implications. In the Appendix we test the sensitivity of our results to different carbon price paths.

2. Methods

In this section, we describe the two models used in the analysis and the equations and assumptions introduced to link them. Finally, we introduce the policy scenarios.

2.1. The Forestry model

The forestry model used in this analysis is the Global Timber Model (GTM) initially developed to study dynamic forest markets and policies (Sohngen et al. 1999). The model contains 200 forest types in 16 regions that can be aggregated into four broad categories: boreal, temperate hardwood, temperate softwood, and tropical. The model assumes there is a social planner maximizing the present value of net consumer surplus over time. It is an optimal control problem given the aggregate demand function, starting stock, costs, and growth functions of forest stocks. 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[2], and the area of forestland at each moment in time. The timber model is forward looking with complete information.

This problem is written formally as:

$$\max \sum_{0}^{\infty} \rho^{t} \left\{ \begin{array}{l} \int_{0}^{Q_t^{*tot}} \left\{ D\left(Q_t^{ind}, Z_t\right) + D\left(Q^{bio}\right) - f\left(Q_t^{tot}\right)\right\} dQ_t^{tot} - \sum_{i} p_m^i m_t^i G_t^i - \sum_{i} C\left(N_t^i\right) - \\ \sum_{i} R^i \left(\sum_{a} X_{a,t}^{i} \right) + CC_t \end{array} \right\}. \quad (1)$$

Table 1 describes the variables and functions in the social planner's problem. The solution to this social programming problem is equivalent to the solution to a competitive market where consumers maximize utility and suppliers maximize profit.

In this version of the model global, wood demand (Q^{tot}) is represented by the aggregate demand function for industrial wood (like lumber, paper, and plywood) and the demand for woody biomass for energy Q^{wbio}:

$$Q_t^{tot} = Q_t^{ind} + Q^{wbio}. \quad (2)$$

The industrial demand function Q^{ind} is assumed to grow over time as the global economy grows:

$$Q_t^{ind} = A\left(Z_t\right)^{\theta} \left(P_t^{wbio}\right)^{\omega}, \quad (3)$$

where A is a constant, Z is the global income per capita (from the economic model), ϑ is the income elasticity, P^{wbio} is the international price of wood and ω is the price elasticity. For this study Q^{wbio} is determined by the economic model WITCH for each period given the implied P^{wbio} and the price of carbon P^c (Favero and Mendelsohn, 2014).

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[2] 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, unmanaged forests are left in a natural state unless global timber prices are high enough to justify management. 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.

$D\left(Q_t^{ind}, Z_t\right)$ = global demand function for timber

$D\left(Q^{bio}\right)$ = global demand function for woody biomass

$f\left(Q_t^{tot}\right)$ = cost function for harvesting timber or biomass

Z_t = global consumption per capita

p_m^i = cost of a unit of management for forests type i

m_t^i = management intensity for forests type i

G_t^i = area of land regenerated in type i

$C\left(N_t^i\right)$ = cost function to establish new high value plantations

$X_{a,t}^{i}$ = area of forest in each age class a and type i

$R^i\left(\sum_a X_{a,t}^{i}\right)$ = rental cost function for holding land in forest type i

CC_t = carbon payment for forest sequestration

Table 1: Variables and functions in GTM

The total wood supply comes from the forested regions of the world. We assume there is an international market for timber that leads to a global market clearing price. For instance, Sedjo et al. (2015) shows that a strong and continuing demand for bioenergy in the US would drive the price of fuel wood to equal that of pulpwood. 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 (Favero and Massetti 2013). If woody biomass is going to directly compete with wood products, competition for supply will equilibrate their prices.

The model takes into account the competition of forestland with farmland using a rental supply function for land (Sohngen and Mendelsohn, 2003). In Equation (1) R_i is the rental cost function for holding timberland and X_i is the area of land in age class *a* and time *t* for i-forest type. 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. [3]

Carbon storage is counted in four main pools: aboveground forest carbon, forest products, soil carbon, and slash carbon.

Aboveground carbon (C^{ab}) accounts for the carbon in all trees components (including roots) as well as carbon in the forest understory and the forest floor. It is a function of the stock of land *X*, the growth function *V* and the management intensity (m_{t0}):

$$C_{a,t}^{ab} = \omega_a V_{a,t}\left(m_{t0}\right) X_t , \tag{4}$$

Where ω_a is the conversion factor that converts forest biomass into carbon. It is specific to each forest type and differs by age class.

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[3] One of the key parameters likely to affect the effects of woody biomass demand on forestland in climate mitigation scenarios is the price elasticity of land supply. The literature presents a range between 0.2 and 0.5 (Sohngen and Brown, 2006; Lubowsky et al, 2006; Kim et al. 2010). The previous version of the timber model assumed a single price elasticity coefficient for both expanding forestland into farmland and for the border between natural and managed forest. In this new version of the model we assume higher elasticity for natural forestland (0.5) than managed forestland (0.25).

Carbon in forest products (HC) is estimated by tracking forest products over time and it is calculated as follows:

$$HC_t^i = \sum_a \left(\kappa^i V_{a,t}^i (1-\vartheta) H_{a,t}^i \right), \tag{5}$$

where κ is the factor to covert harvested biomass for market into carbon stored in products and ϑ is the portion of wood used in the energy sector. For simplicity we assume κ= 0.30, that 30% of the material entering wood product markets is stored permanently (Winjum et al. 1998). In contrast, the carbon in wood that is used for energy production is released at the time of burning, unless the carbon is captured and stored.

We do not rent the carbon stored in forest soils because they are not affected by forest management (see Johnson, 1992 and Johnson et al. 2001). We do, however, value the change in carbon when land switches between forests and agriculture or vice-versa. Thus, we correctly capture the marginal change in carbon value associated with management or land use changes in our model. When land use change occurs, we track net carbon gains or losses over time:

$$SOLC_{t+1}^i = SOLC_t^i + SOLC_t^i \left(\mu^i \right) \left[\frac{\left(\overline{K}^i - SOLC_t^i \right)}{SOLC_t^i} \right], \tag{6}$$

where $SOLC_t^i$ is the stock of carbon in forest soils of type i in time t. The initial soil carbon levels are specific to each region. The value of K, the steady state level of carbon in forest soils, is unique to each region and timber type. The parameter μ is the growth rate for soil carbon. The same equation is used when land converts from forest to agriculture but with reverse initial carbon and steady state numbers (Daigneault et al. 2012).

We measure slash carbon (AS) as the carbon left over on site after a timber harvest. Over time, the stock of slash builds up through annual additions, and decomposes. Decomposition rates differ, depending on whether the forest lies in the tropics, temperate, or boreal zone.

Because we want to assess the interaction of the two CDR techniques, we include in Equation (1) the returns for forest carbon sequestration SEQU (CC_t). As in Sohngen and Mendelsohn (2003), we use a rental scheme whereby carbon stocks in forests are rented during the time period that the carbon is stored, and carbon transferred to long-lived wood products is paid the carbon price at harvest time. This approach, while efficiently equivalent to the tax and subsidy scheme proposed by van Kooten et al. (1995) has different distributional consequences for landowners. For this paper, the rental approach is perhaps more appropriate logistically because some forests may at first sequester carbon but then later be harvested for biomass energy and carbon capture and storage. Thus, the carbon sequestered in forests is temporary, and by renting it is paid only during the time it is stored. Carbon that is captured after burning and stored underground is assumed to be permanent and is paid the carbon price at the moment of storage.

The rental value for carbon, R_t, is:

$$R_t^c = (r-n) P_t^c , \tag{7}$$

where *r* is the interest rate and *n* is the rate of increase of the price of carbon:

$$n_t = \left[dP_t^C / dt \right] / P_t^C . \tag{8}$$

The rental payment creates an incentive to convert land to forest (afforest), to grow forest more quickly (increase management intensity), to reduce the conversion of natural forests to managed forests, and to extend the rotation of forests (possibly indefinitely). The carbon payment to the forest owner is for every stock of forest carbon. The total carbon payment equals the rent on carbon in temporary aboveground stocks and the carbon price multiplied by the more permanent carbon stored in wood products, slash pools[4], and soils ($\Delta SOLC_t = SOLC_{t+1} - SOLC_t$). Harvesting is assumed to have no effect on soil carbon if the land remains in forests but causes a decline in soil carbon if there is a change in land use.

Thus, the form for CC_t is:

$$CC_t = R_t^c C_t^{ab} + P_t^c \left(0.3 \cdot HC_t + \Delta SOLC_t + \alpha^i AS_t^i\right) \tag{9}$$

2.2. Economic mitigation model

The economic model used for the analysis of mitigation is WITCH – (World Induced Technical Change Hybrid). It is a regional model structured to provide normative information on both the optimal response of world economies to climate damage[5] (cost-benefit analysis) and the optimal use of climate mitigation technologies (cost-effectiveness analysis) (Bosetti, Massetti and Tavoni 2007; Bosetti et al. 2006; 2009). In this paper, we explore the optimal cooperative game feature of WITCH.

In WITCH the energy sector is well detailed. Firms in the power sector generate electricity using nine different technologies: oil, coal, gas, nuclear, wind, hydropower, coal with CCS, gas with CCS, woody biomass with CCS. In the power sector the social planner determines investments in power generation capacity for all technologies. The choice of investments in power generation capacity determines the demand for fuels from the power sector and expenditures in operation and maintenance. This kind of detail in the energy sector makes it possible to reasonably portray future energy technology scenarios and to assess their compatibility with the climate stabilization goal. Finally, 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 for our analysis is how WITCH models the demand for BECCS. In this version of WITCH we assume that BECCS is produced with woody biomass in integrated gasification combined cycle (IGCC) power plants with CCS. BECCS power plants can buy woody biomass from the international market at the market clearing price P^{wbio} given by GTM. Under a carbon price scenario, BECCS power plants will be exempted from paying the carbon price since the carbon released during combustion is offset by the carbon captured during the growth of the trees.[6] In addition, the biomass power plants equipped with the CCS technology receive a subsidy for each ton of CO_2 captured and sequestered with CCS.

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[4] The parameter α which varies by forest type (i) takes into account the decomposition rate of carbon in slash.

[5] 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.

[6] Although this is not exactly correct because carbon storage occurs over a long time before the release, from a long-term perspective, the woody biomass burning does not release new carbon but simply releases previously sequestered carbon that was captured in an earlier period in anticipation of future biomass consumption (Sedjo 2011).

Finally, we assume that biomass power plants receive credits for the extra forest carbon sequestered though soil, slash and market carbon[7] (Favero and Mendelsohn, 2014).

Finally, the economic model WITCH includes CO_2 emissions from fossil fuels, from oil extraction, from land use, land use change and deforestation (LULUCF), and emissions of other non-CO_2 gases. CO_2 emissions from fuel combustion are a function of the carbon content of each fuel while emissions from oil extraction are obtained summing emissions from the extraction of each oil type. In the model, the abatement of CO_2 emissions from fuel combustion is endogenously determined by changing the energy mix and the mix of capital, labor and energy. Emissions of other non-CO_2 gases (methane, nitrous oxide, sulfur dioxide, short- and long-lived fluorinated gases) are exogenous while their abatement relies on abatement cost curves. The LULUCF emissions which account for the change in carbon stock in forests in the baseline scenario are from the forestry GTM. We also track regional GHG emissions from fuel used to harvest and transport woody biomass (Favero and Massetti, 2012).

The formal forest carbon sequestration program is assumed to rent carbon sequestered aboveground and pay for additional carbon stored in wood industrial market products, slash carbon, and forest soils (SEQU scenario). The program pays for carbon stored throughout the world's forests and payments are tied to the carbon price.

2.3. The Soft-link

This study relies on a soft link between the integrated assessment model WITCH and global timber model 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) and to estimate the indirect effect of BECCS on forest sequestration (Favero and Mendelsohn, 2014).

For each carbon price path WITCH generates the demand for woody biomass for BECCS at each time period, the demand for forest carbon sequestration (SEQU) and the global consumption per capita which drives the global demand for industrial timber products in the forestry model. The quantity of woody biomass needed to meet bioenergy demand[8], the price of carbon and the global consumption per capita are included in the forestry model. The forestry model then solves for the international price of wood and the carbon price over time that could supply the total harvest of wood and the amount of forest carbon sequestration credits for each year. The international price of wood is then entered back into WITCH which generates a new quantity of woody biomass demanded, the new demand of forest credits and new global consumption per capita.

For each mitigation strategy, WITCH assures that the outcome takes into account the competition between woody biomass and other mitigation options. The forestry 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. We assume no uncertainty in these projections and that the market is forward looking. There is a signal in advance that reveals future prices. Thus, the model plants forests in advance of future wood demand.

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[7] These values take into account that an increasing demand for wood for the energy sector will reduce the demand for industrial wood for the industrial sector and therefore the amount of carbon stored in its products.

[8] On average, 1 m^3 of timber produces approximately 8.8 MMBtu of energy (Daigneault et al. 2012).

Finally, to make the two models consistent, several adjustments were made. First, the different regions had to be matched: in GTM forest types are aggregated into 16 regions: US, China, Brazil, Canada, Russia, EU Annex I, EU Non-Annex I, South Asia, Central America, Rest of South America, Sub-Saharan Africa, Southeast Asia, Oceania, Japan, Africa and Middle East, East Asia; while in WITCH 13 regions interact. The regional disaggregation is similar therefore only minor adjustments were needed. Second, WITCH has 5-year time steps and the forestry model has 10-year time steps. To link the two models, we interpolate from the 10 years biomass price steps of GTM, a set of 5 year price steps for WITCH. The models are assumed to be linked (in equilibrium) when the quantity of woody biomass demanded by the economic model changes less than 5% between iterations following the approach used in Tavoni, Sohngen and Bosetti (2007) . The result reveals a dynamic path of timberland, management intensity, and harvests in GTM, a path of carbon and timber prices and forest carbon sequestration in both models, and a path of carbon mitigation and technologies in WITCH.

2.4. Policy Scenarios

In this study we start with a baseline scenario (BAU scenario) with no mitigation which leads to a level of GHG concentration in the atmosphere of 951 ppm and radiative forcing equal to 6.6 W/m^2 in 2100 (Carraro et al. 2012). For the baseline case, the carbon price is equal to zero.

We then simulate an ideal policy framework in which all countries agree to implement a path of global carbon prices which stabilizes the average global temperature to 2°C by 2100. All users of fossil fuels pay a price proportional to the CO_2 content of each fuel and receive a credit if they capture and store CO_2 with CCS or if they increase carbon sequestration in forests. For the forest carbon sequestration policy, we assume an international climate control regime under which sequestration policies are an option given the global carbon price. The amount of forest CDR used is determined endogenously by WITCH. The analysis only uses the forest CDR if it is cost-effective.

As described in Table 2, we follow three alternative CDR regimes: (1) BECCS-only; (2) SEQU-only; and (3) BECCS+SEQU. The BECCS-only and SEQU-only scenarios are used to compare the implications on forestland and carbon flux of the two CDR options under the same carbon price path[9]. Then, the BECCS+SEQU scenario is compared to the two individual CDR scenarios. The comparison evaluates the effectiveness of each scenario, the timing, and the effect on land use.

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[9] We assume a fixed CO_2 price schedule that meets the 2°C target.

CDR regime	Description
BAU	Baseline scenario without climate policy/carbon price.
BECCS-only	BECCS is the only CDR option available since forest carbon sequestration is not value directly. BECCS power plants receive both a subsidy for each ton of CO_2 captured and sequestered with CCS and an indirect subsidy for each ton of extra-sequestration produced.
SEQU-only	Forest carbon sinks are the only way to achieve a net removal of CO_2 from the atmosphere since we assume that CCS is not available for biomass power plant. Under this option, countries can pay forest rental and buy forest carbon credits in the international market.
BECCS+SEQU	Both BECCS and SEQU are used together.

Table 2 Scenarios

3. Results

3.1. BECCS-only vs. SEQU-only

In this section we assess the implications of having only one forest-related CDR option. We assume that the overall mitigation strategy in all cases meets the 2°C target. In the BAU scenario, global forestland remains somewhat constant over the century with a slight reduction from 3,466 million ha in 2010 to 3,229 million ha by the end of the century. Temperate regions would experience slight afforestation and tropical regions would experience slight deforestation due to the increase in global cropland demand.

Either the imposition of a carbon payment for forest sequestration or the demand for wood for BECCS provides incentives for landowners to increase forestland. In both scenarios, deforestation shifts immediately to afforestation because carbon prices immediately create a strong market incentive to expand the stock of carbon held by land owners.

In the BECCS-only scenario, forestland expands in anticipation of future biomass burning. For instance, by 2020, forestland expands by 12% relative to the BAU. To support a supply of about 50 EJ/yr of woody biomass will require 1,652 Mha of additional forestland by 2100 relative to BAU. In addition to an increase in total forestland, the BECCS-only scenario causes a reduction of 200 Mha of natural forest area by 2100, as natural forests are converted to managed forests to supply wood for bioenergy markets.

For any given carbon price, the SEQU-only program produces a higher demand for forestland than the BECCS program. To support an average of 8.9 $GtCO_2$/yr of carbon sequestration in forests over the century, SEQU requires conversion of 1,932 Mha of land into forests. SEQU-only also increases the area of natural forestland, causing an additional 500 Mha of forests to be preserved from harvesting by 2100.

There are several important differences between the two programs. SEQU ramps up more quickly than BECCS and causes timberland to expand immediately. The BECCS program only starts in the second half of the century so that initial forestland expands only slightly in anticipation. However, by the end of the century, the managed timberland needed to fuel BECCS is larger than the managed timberland under SEQU (Figure 1a). The BECCS program, however, does nothing to increase the value of natural forests and so natural forest area gradually declines over time under the BECCS scenario. By 2100, there is 50% more natural forest in the SEQU program compared to the BECCS program. Counting natural forests the overall area of forestland is greatest under SEQU (Figure 1b).

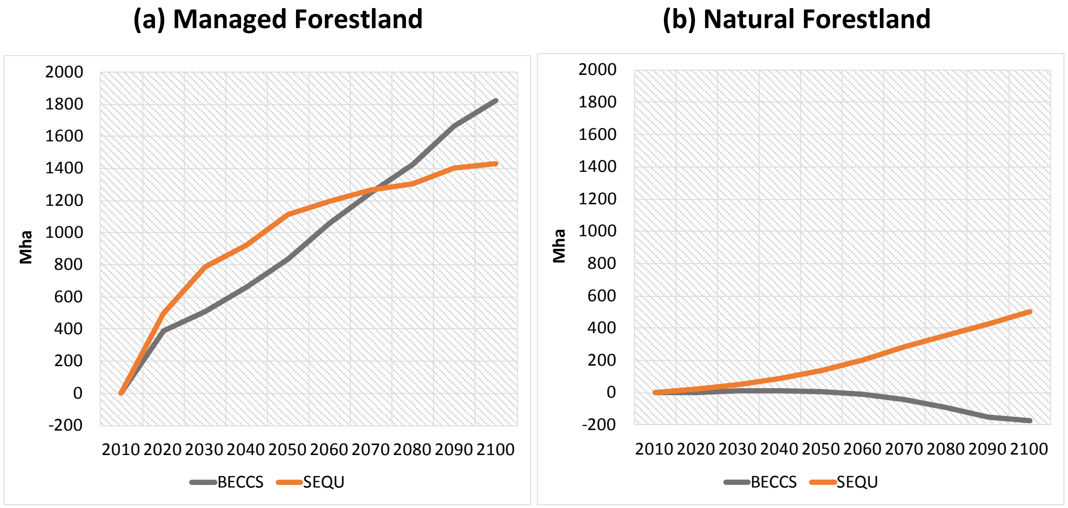


Figure 1: (a) Managed and (b) Natural forestland change under the BECCS-only and SEQU-only scenarios relative to BAU scenario (Mha)

The forest CDR methods have different regional effects (Figure 2). Under SEQU more forestland is added in tropical regions as compared to BECCS. These are relatively low cost lands that can rapidly sequester carbon under the lower carbon prices that prevail in the early part of the century. As carbon prices rise and BECCS becomes economically feasible, the BECCS scenario begins devoting more land to forests in tropical regions, reducing the difference between the scenarios. The temperate zone has slower growing and longer-lived forests. It turns out that the potentially high value of forests in the long-run with the BECCS program provides a stronger incentive to increase forestlands in the temperate zone than the SEQU program.

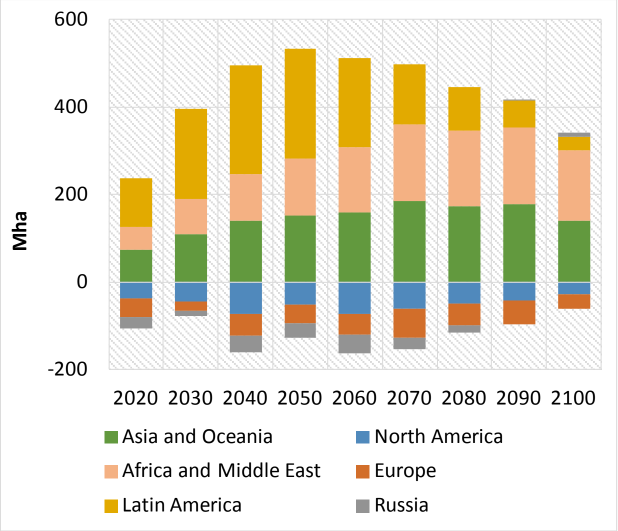


Figure 2: Net difference in total forestland by region, SEQU-only minus BECSS-only. A positive numbers indicates that there is more land in forests in SEQU-only compared to BECCs-only.

In both CDR scenarios, the carbon price leads to net carbon removal from the atmosphere: carbon is either biologically sequestered in forests or geologically sequestered with CCS.

For the period 2020-2100, the flux of carbon added to the forest under SEQU will average 8.83 $GtCO_2$/yr. About 89% of this carbon will be in aboveground carbon (standing biomass). The BECCS program will remove an average of 8.45 $GtCO_2$/yr over the same time period, and about 31% of this carbon will be stored underground via CCS, 21% through fossil fuels substitution, and the remaining 48% through sequestration in forest pools (Figure 3). Fewer wood products are produced in the BECCS-only scenario, so compared to the business as usual, less carbon is stored in wood products. Similarly, slash pools decline relative to the business as usual under SEQU-only while slash pools rise substantially under BECCS-only due to the large increase in harvesting.

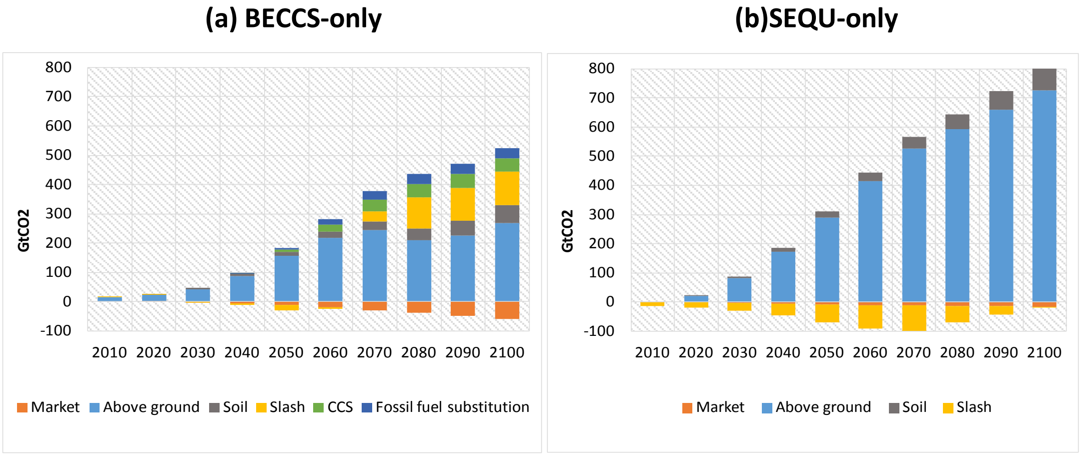


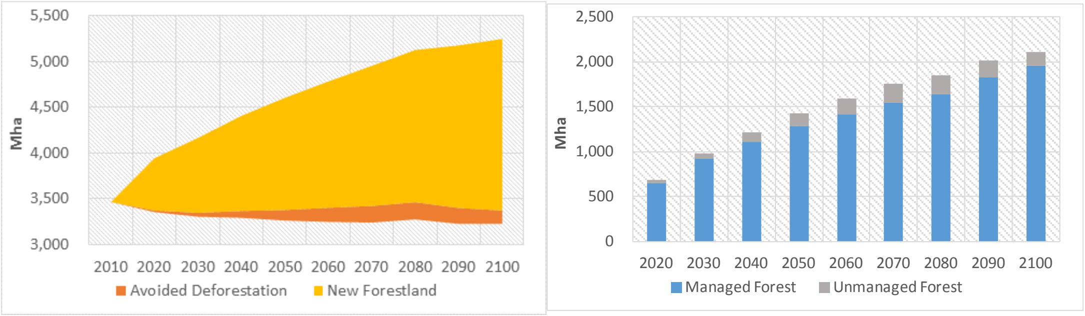
Figure 3: Changes in carbon stock for SEQU and BECCS programs relative to BAU ($GtCO_2$)

3.2. BECCS+SEQU

In this section we examine BECCS+SEQU using both CDR technologies together. Even with a low initial global carbon price of \$14/tCO_2, there is a sufficient incentive with the SEQU portion of the program to start immediately. In contrast, carbon prices reach \$235/tCO_2 before the BECCS portion of the program to become feasible in 2055. Both programs become larger over time as carbon prices rise.

The advent of these two programs together reduces deforestation and increases afforestation. The increasing demand for forestland under sequestration and woody biomass encourages considerable cropland to shift into forestland: 1,730 Mha of current cropland is shifted into new forestland by 2100 (Figure 4a). The BECCS+SEQU program causes an increase in deforestation in the latter part of the century, so in 2080 187 Mha of land have been saved from deforestation, but around 40 Mha of this is lost to deforestation by 2100.

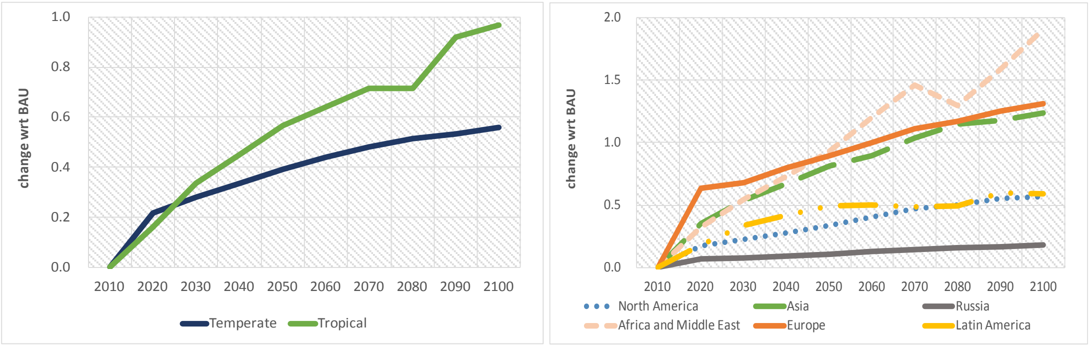
While total forestland increases in the BECCS+SEQU scenario, managed forestland basically doubles, increasing by 95% in 2050 and by 100% in 2100, relative to the BAU (Figure 4b). Management intensity, as measured by growth per ha, increases by 57% in managed forest, signifying substantial intensification. Although the area of natural forests is less than in the SEQU-only scenario, the area of natural forests actually expands, though modestly, in the BECCS+SEQU scenario relative to the BAU. This suggests that the value of carbon in many natural forests is relatively high, and it would be efficient to preserve those lands, even with a strong BECCS program.


(a)

(b)

Figure 4: (a) Change in forestland and (b) Increase in managed and natural forestland with BECCS+SEQU relative to the BAU scenario

Although all countries increase their forestland under BECCS+SEQU, the highest percentage increase in forestland occurs in tropical regions (Figure 5a). Boreal forestland has the lowest percentage response to BECCS+SEQU. In terms of regional effects, Africa has the highest rate of increase in forestland under BECCS+SEQU with South East Asia and Europe tied for a close second (Figure 5b). Breaking down the regional response by each part of the program, half of the global supply of forest sequestration comes from Latin America and South East Asia. In contrast, almost half of the wood for bioenergy production comes from Europe and the United States.


(a)

(b)

Figure 5: Percentage change in (a) temperate and tropical forestland and (b) regional forestland under the 2C policy scenario with both CDR options available with respect to the BAU scenario 2010-2100

BECCS+SEQU stores carbon in aboveground biomass, slash, soil and geological storage (CCS) (Figure 6). In the first half of the century, most of the accumulation is in aboveground biomass as trees are planted for future biomass burning and as carbon is stored in trees. There is virtually no change in carbon stored in the soils but a little carbon is lost in reduced slash. After 2070, the biomass burning increases substantially. In the second half of the century, there is some carbon stored in soils, carbon is stored underground through CCS, carbon is saved by biomass burning (reducing fossil fuel consumption), and there is more carbon in slash. However, above ground carbon shrinks and carbon stored in market products shrinks slightly. [10]

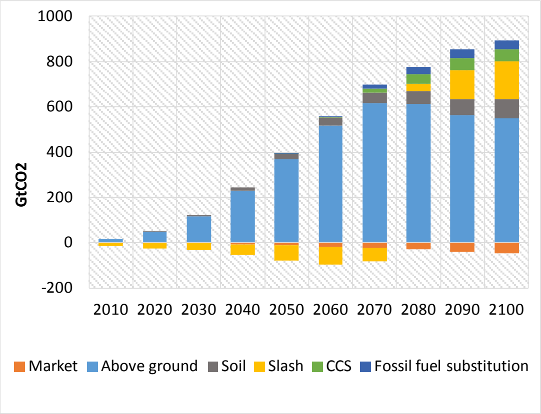


Figure 6: Change in carbon stock in the 2°C policy scenario with BECCS+SEQU relative to BAU

What is the difference between BECCS+SEQU and just SEQU? More carbon is initially stored in forests under BECCS+SEQU in anticipation of biomass burning relative to SEQU (Table 3). But once biomass burning starts in 2055, the extra carbon is harvested and burned which produces in 2100 a reduction in the total forest sequestration in the BECCS+SEQU with respect to the SEQU-only. For 2020-2100, the long term carbon stored in the forest falls from an average of 8.8 $GtCO_2/yr$ to 8.3 $GtCO_2/yr$. However, including the amount of carbon removed by BECCS (CCS and fossil fuel substitution) leads to more overall carbon removal, 12.27 $GtCO_2/yr$.

Scenarios	Carbon Pools $GtCO_2$						Total CO_2 removal
	Aboveground	Market	Soil	Slash	CCS	Fossil fuel substitution	
BECCS-only							
2050	156	(11)	15	(18)	7	5	154
2100	268	(58)	62	114	47	34	466
SEQU-only							
2050	290	(9)	20	(62)	0	0	240
2100	725	(16)	77	(5)	0	0	782
BECCS+SEQU							
2050	370	(12)	25	(69)	--	--	314
2100	548	(47)	85	168	53	39	846

Table 3: Additional carbon stock removed from the atmosphere in 2050 and in 2100 under the three CDR regimes

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[10] The demand for wood for BECCS leads to a rapid increase in the international price of wood relative to the BAU. The forward looking forestry 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 2060.

BECCS+SEQU encourages more land to be converted to forestland than SEQU-only. By 2100, BECCS+SEQU has 180 Mha more forestland than SEQU alone. BECCS+SEQU encourages more management in forests than SEQU-only. BECCS+SEQU has 527 Mha of additional managed forests of which 42 Mha is additional plantations. These plantations are an important supply of timber, biofuels and carbon, even though they cover a tiny fraction of forestland. However, there is 347 Mha less of natural forestland in the BECCS+SEQU program than in SEQU-only. So the BECCS+SEQU program is not as effective for forest conservation as SEQU-only.

What is the difference between BECCS+SEQU and just BECCS? Adding a forest sequestration program to BECCS delays the start of the BECCS program from 2040 to 2055 (Figure 7a). Sequestration is a more competitive mitigation strategy than BECCS at the lower carbon prices earlier in the century. While sequestration dominates, the carbon incentives in the SEQU program shift forests towards older age classes in order to increase carbon storage. The sequestration component of BECCS+SEQU increases average wood growth as it pushes the forest away from a Faustmann rotation and towards a maximum sustained yield rotation. The increase in long term wood supply lower the long term price of wood compared to a BECCS-only program (Figure 7b). So the wood product industry does far better under BECCS+SEQU than BECCS-only. In the long run, the lower price of wood is also helpful to biomass burning. The biomass burning component of BECCS+SEQU is eventually slightly larger than in BECCS-only.

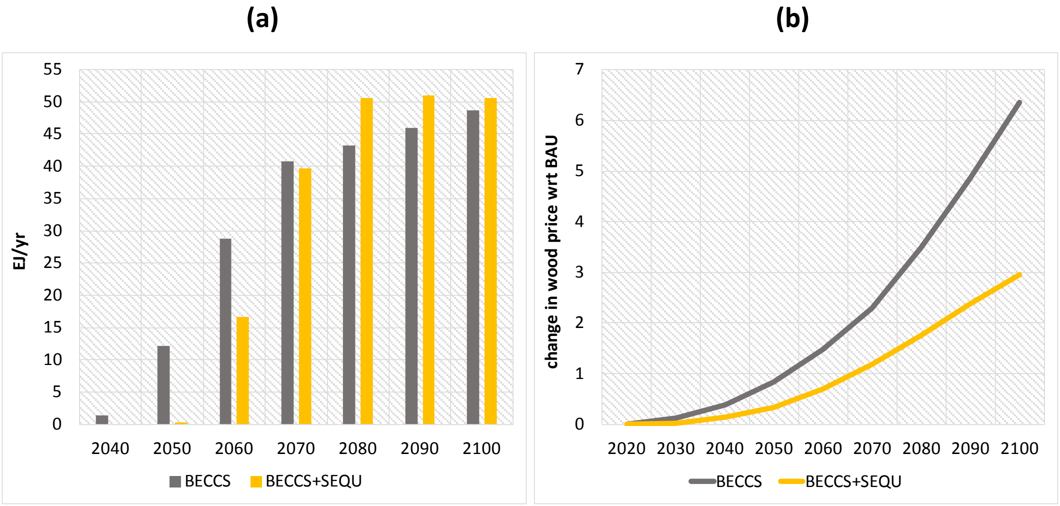

Figure 7: (a) Woody biomass burning and (b) Wood price changes with BECCS-only and BECCS+SEQU

3.3. Implications for mitigation

In the last section, we examine the share of overall mitigation that each of the three forest CDR options is expected to contribute to the 2°C target by 2100. In the BECCS-only scenario, the BECCS program makes only a small contribution to mitigation in the first half of the century but makes a much larger contribution in the second half of the century. Overall, it provides 16% of cumulative mitigation by 2100. The SEQU-only program provides a steady flow of carbon removal throughout the century leading to an overall share of 20% of total mitigation by 2100. The BECCS+SEQU regime starts with the steady flow of carbon sequestration in the first half of the century and then expands in the second half of the century with CCS and fossil fuel substitution (Figure 8). The BECCS+SEQU share of overall mitigation through 2100 is 26% which is split almost evenly between forest sequestration and BECCS.

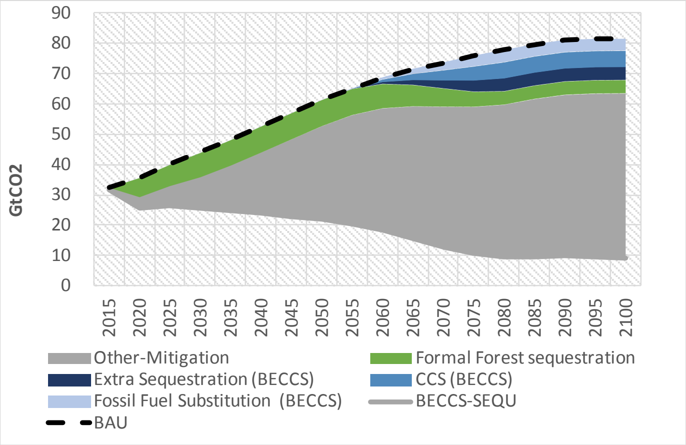

Figure 8: Share of total mitigation from BECCS+SEQU (GtCO2)

4. Conclusions

This paper combines the global dynamic forest model (GTM) with the global mitigation model WITCH to study the optimal use of forestland under a 2°C mitigation target. The soft-link of the two models allows us to combine the demand function for carbon storage and bioenergy from WITCH with the wood supply from GTM to estimate a more sophisticated economic model of bioenergy. The model captures not only land use decisions concerning managed and natural forest but also dynamic forest management decisions, including planting, rotation length, and management intensity. These decisions differ dramatically across the world's forests, and thus are critically important to include when modeling the role of forests in climate mitigation strategies.

Using these modeling tools, the paper first evaluates the effects on forestland and carbon flux of using either sequestration (SEQU-only) or biomass burning (BECCS-only). Results shows that both SEQU-only and BECCS-only initially slow deforestation and increase afforestation throughout the 21st century. The SEQU-only program has an immediate effect because it is a low cost mitigation option. BECCS tends to affect carbon storage only later in the century because it is much more expensive. Both programs increase the value of managed forest land leading to managed forestland expanding over the century. However, only SEQU provides an additional incentive for natural forestland which increases in this program. In contrast, the BECCS-only program causes a 12% reduction in natural forest area over the century relative to BAU. Tropical forests are more responsive to sequestration incentives and provide most of the additional carbon under SEQU. In contrast, temperate forests respond most vigorously to biomass burning and provide most of the wood supply for BECCS.

Given the same carbon price schedule, SEQU-only has a slightly lower cost of carbon mitigation compared to BECCS-only, and so provides slightly more carbon, 8.83 $GtCO_2$/yr than BECCs-only, 8.64 GtCO2/yr over the century. Under SEQU-only most of the extra carbon is stored in aboveground biomass, with small portions sequestered in market, slash, and soil components. In contrast, with BECCS-only less than half of the stored carbon is in aboveground carbon with some stored in slash. The remaining stored carbon under BECCS is underground (CCS) and avoided fossil fuel burning (biomass burning).

The study also finds that BECCS+SEQU is more cost effective than relying on BECCS-only or SEQU-only. BECCS alone can remove an average of 8.7 $GtCO_2$/yr, SEQU alone can remove 8.9 $GtCO_2$/yr, but BECCS+SEQU removes 12.3 $GtCO_2$/yr given the carbon price schedule tested. Sequestration and BECCS work well together. Sequestration builds an initial large forest supply that BECCS later exploits. Adding the SEQU program to BECCS reduces the price of wood relative to the BECCS-only scenario. This is beneficial to both the wood product industry and BECCs, dramatically lowering the price of wood in the second half of the century. The use of both mechanisms leads to a large expansion of global forestland at the expense of marginal cropland. Most of the increase is in managed forestland. The sequestration component initially increases natural forestland as well but when the wood bioenergy program starts, this additional natural forestland is largely turned into managed forestland to supply BECCs.

We assume throughout this paper that a carbon sequestration program can be administered. The implementation of a formal sequestration program, however, faces important institutional challenges (Mendelsohn, Sedjo, and Sohngen 2012). In many parts of the world, there are not well-defined property rights to the carbon in forests. A cost-effective sequestration program needs to be global with a single carbon price. Inexpensive mechanisms to monitor forest carbon stocks need to be implemented. Finally, many sequestration programs assume additionality which implies public knowledge of business-as-usual forest management of every plot in the world which may be unrealistic (Andersson and Richards 2001; Richards and Stokes 2004; Andersson et al. 2009; Plantinga and Richards 2010; Mason and Plantinga 2013).

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