A System Dynamics Study of Carbon Cycling and Electricity Generation from Energy Crops

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Abstract

The Climate Stewardship Act, a global warming mitigation policy calling for a cap-and-trade program, was reintroduced in the United States Senate this year. The Energy Information Administration analyzed the implications of the bill and found that under such a policy renewable energy will increase, with the strongest response coming from biomass energy. Dedicated energy crops are one source of biomass that is expected to contribute significantly to the future biomass energy supply. This paper describes a system dynamics model of the carbon impacts from a dedicated energy crop. The work relies on another carbon accounting model, GORCAM, which uses spreadsheet modeling to investigate various land management regimes. We were able to reproduce the GORCAM results for a 20-year harvest rotation; we then simulated several different harvesting intervals to gain insight into the carbon impacts of these rotations. Our results show that using energy crops to displace coal in electricity generation will have greater impacts on reducing atmospheric carbon than simply planting the crop for carbon sequestration. Furthermore, the harvest interval with optimal carbon benefits was found to be 9 years. These results agree with previous work that found long-term benefits were greater for scenarios where trees were planted for energy generation rather than specifically for carbon sequestration.

Background on WSU Research

This paper describes a computer model to simulate carbon uptake and carbon emissions from lands planted with crops grown specifically for power generation. The model was developed at Washington State University (WSU) as part of a project for the National Science Foundation (NSF). The goal of the NSF research is to develop innovative simulation methods for interdisciplinary analysis of electricity markets. The WSU research makes use of the system dynamics modeling method explained in texts by Ford (1999) and Sterman (2000). We have combined the system dynamics method with power systems engineering methods to provide a unique capability to simulate long term changes in deregulated power systems (Dimitrovski et al., 2005). The new capability will be demonstrated with the WECC as a reference system. WECC stands for the Western Electric Coordinating Council, an electric reliability organization for the western United States, Canada and Mexico. (This and other acronyms used in this paper are listed in Table 1.) Our demonstration will focus on the impact of a carbon allowances market like the one envisioned in S.139, the Climate Stewardship Act of 2003.

The main analysis of S.139 will be conducted with the newly developed model of the WECC. This analysis will be informed by two, separate models which focus on renewable generating resources which may respond strongly in a S.139 scenario. One model focuses on increased generation of electricity from wind (Ford et al., 2005), with a particular emphasis on the role of TGCs, Tradable Green Certificates. The second model is described in this paper. It focuses on increased generation of electricity from power plants fueled by dedicated energy crops (ECs).

Table 1. List of acronyms and abbreviations in this paper

ECs	Energy Crops
EIA	Energy Information Administration
GHG	Green House Gasses
GORCAM	Graz-Oak Ridge Carbon Accounting Model
NEMS	National Energy Modeling System (used at EIA)
NSF	National Science Foundation
ORNL	Oak Ridge National Laboratory
RGGI	Regional Greenhouse Gas Initiative
RPS	Renewable Portfolio Standard
S.139	Senate Bill 139: The Climate Stewardship Act of 2003
TGC	Tradable Green Certificate
WECC	Western Electricity Co-ordinating Council
WSU	Washington State University

Organization of the Paper

The paper begins with background on the carbon allowance market envisioned in S.139 and the potential for major increases in biomass electricity generation. We then describe GORCAM, a spreadsheet model that can be used to calculate carbon emissions associated with dedicated energy crops. We have adapted selected portions of the GORCAM model to operate with Vensim, the system dynamics software used in the NSF project. We describe the model structure and parameters, and we demonstrate that the new model reproduces benchmark results from GORCAM. We use the model to examine changes in harvesting cycles. We believe that land managers will need some flexibility in choice of crops and in the harvesting cycle if they are to deliver the energy crops to keep pace with the projected growth in biomass generating capacity. We have selected poplars as an example of a short rotation crop, and we simulate the carbon emissions associated with harvesting the poplars on different schedules.

Background on the Climate Stewardship Act

Climate change mitigation policies exist on many levels, from the global-scale Kyoto Protocol to state-level programs, such as Renewable Portfolio Standards (RPS) and the Regional Greenhouse Gas Initiative (RGGI). In February 2005, Senators McCain and Lieberman reintroduced the Climate Stewardship Act (S.139) to the Senate. This bill was rejected in an October 2004 vote, but received significant support. S.139 would initiate a cap-and-trade program for greenhouse gas emissions. A cap to bring emissions back down to 2000 levels would start in 2010. The initial cap would be 621 million metric tons of carbon equivalents (MMTC) for the electricity sector. (This and other units used in this paper are listed in Table 2.) The original S.139 calls for another phase starting in 2016 to bring the cap down to 1990 emissions levels (492 MMTC), but the second phase target has been eliminated in more recent proposals.

Entities that emit over 10,000 MTC per year are required to participate in the program. For each metric ton of GHG emitted, a covered entity would have to turn in an allowance or pay a penalty. Allowances for each metric ton of emissions would be distributed based on the cap (the details of allocations are, as of yet, undetermined) and then be available for purchase or trade among the entities. The plan includes banking and limited borrowing to provide flexibility in compliance. This market-based approach rewards those entities that can reduce emissions beyond what is required by allowing them to sell extra allowances. Proponents of this approach often point to the cap-and-trade market for SO_2 emissions, a market considered by some to be a successful application of emissions trading (Field and Field, 2002).

Table 2. List of units used in this paper.

BTU	British Thermal Unit, a measure of energy
kw	kilowatt, a measure of electric power
kwhr	kilowatt hour, a measure of electric energy
GW	Gigawatts, a measure of electric power (1GW = 1000 MW)
GWhr	Gigawatt hour, a measure of electric energy
MTC	Metric Tons of Carbon equivalent
MMTC	Million Metric Tons of Carbon equivalent
MW	Megawatt, a measure of electric power (1 MW = 1000kw)
MWhr	Megawatt hour, a measure of electric energy
tC	metric ton of Carbon

Several studies were undertaken to assess the impacts of S.139. One of the most detailed and carefully documented studies was conducted by the Energy Information Administration (EIA, 2003). The EIA used the National Energy Modeling System (NEMS) to investigate what effect S.139 would have on a range of concerns. Among other things, the report addressed: effective delivered fuel prices, allowance prices, fuel mix shifts and macroeconomic consequences. Some of the major findings were that the electricity industry would play the largest role in emissions reductions, and that effective delivered fuel prices for high-carbon fuels, such as coal, would be prohibitively expensive. The electricity sector in the United States is a major polluter, accountable for 39% of GHG emissions (EIA, 2004). According to the EIA analysis of S.139, the electricity industry is expected to reduce emissions by almost 80% if the bill were enacted. This would be achieved, in large part, through a fuel switch from coal to less polluting fuel sources such as renewables.

By 2025 (the ending year of the EIA analysis) renewable energy is expected to be 143% higher with S.139 than the base case without a carbon allowance market. According to the NEMS model, wind and biomass have the most potential for growth.

- Installed wind capacity was around 1.6 GW in the year 2000. By the year 2025, the EIA expects 9.3 GW in a reference case and 79.9 GW in the S.139 case. The S.139 scenario envisions wind capacity growing by 50-fold in 25 years.

- Biomass capacity is projected to grow in a substantial manner as well. Installed biomass capacity was 5.2 GW in the year 2000. By the year 2025, the EIA expects 10.6 GW in a reference case and 66.4 GW in the S.139 case. The S.139 scenario envisions biomass generating capacity growing by 12-fold in 25 years.

Dedicated Biomass as a Carbon Neutral Energy Source

Biomass used for electricity generation falls into four main categories of source material: agricultural residues, forestry residues, urban/mill waste and energy crops (Haq, 2002). Agricultural residues are the plant material left behind after a crop, such as wheat, is harvested. Similarly, forest residues are the remaining tree parts after a forest has been logged. In both of these cases some of the residues are collected and used for energy generation, but a certain amount must be left behind in order to replenish the soil. Urban and mill wastes refer to the by-products of industrial processes that would otherwise be disposed of. Energy crops (ECs) are herbaceous and woody plants and trees that are grown specifically for energy generation, with the most prominent species being hybrid poplars, hybrid willows and switchgrass. Grasses can be harvested yearly, while woody plants and fast-growing trees are allowed to grow for several years before being harvested. Growing crops specifically for energy is referred to as a "closed-loop process" because the carbon that is emitted by burning the biomass was removed from the atmosphere by the crop as it assimilated the carbon during its growth (Haq, 2002). This results in energy generation that is almost carbon neutral (some greenhouse gases are released in transportation and crop production, but this represents only 5% of the total carbon that goes through the system (Mann and Spath, 1997)). Thus, the generating companies would not have to purchase allowances for carbon emissions from burning ECs under S.139.

An Oak Ridge National Laboratory study of the biomass potential for the country found a total of 512 million dry tons of biomass feedstock could be available for energy generation each year, the largest portion of which would be from ECs, followed closely by agricultural residues (http://bioenergy.ornl.gov). Electricity capacity from biomass could reach 70 GW by 2020 (Haq, 2002). For biomass to reach its full potential and meet projected contributions to the electricity supply, dedicated energy crops will need to be developed.

Currently, there is no market for ECs (Haq, 2002), yet ECs have several advantages over the other biomass resources. Many environmental, social and economic benefits are associated with energy crops. They provide habitat for wildlife that otherwise would not exist and reduce soil erosion (Paine et al., 1996). Furthermore, they can be grown with lower fertilizer and pesticide inputs than other crops (Easterly and Burnham, 1996). Coppicing further reduces management inputs. This is a production method that leaves behind a stump from which new growth can occur, thus avoiding the need to replant the entire crop. In the case of poplars, the tree can be coppiced for 20 years before replanting is necessary (Nonhebel, 2002). Social and economic benefits may also be realized with the planting of an energy crop, especially in rural areas. Biomass in all forms is typically used locally because of the high transportation costs. Therefore, an area that commits to energy crop plantations will benefit from the creation of jobs, income from the crop (especially if the land is ill- suited for a high-profit crop) and lower electricity rates (Paine et al., 1996). In addition, as opposed to waste and residue collection, dedicating land to energy crop production allows for a quantifiable supply that power plants can count on (Easterly and Burnham, 1996).

Large amounts of land will be needed for energy crop production. The ORNL estimates that 42 million acres (or 10%) of cropland (including land that is "currently planted to traditional crops, idled, in pasture, or in the Conservation Reserve Program") could be made available for energy crop production (http://bioenergy.ornl.gov). Many of the proposed locations for energy crops, particularly poplar are on marginal or protected lands. The federal government administers the Conservation Reserve Program which "removes environmentally sensitive cropland from production in exchange for annual rental payments" (Walsh et al., 1996, p.1). These lands are prime locations for energy crops for two reasons. First, ECs are more environmentally friendly than other agriculture so the land would in effect continue to be conserved. Second, payments made to farmers to not farm the land could be reduced or used as a subsidy for the energy crop, making them more competitive with inexpensive energy sources like coal (Walsh et al., 1996). Paine et al. (1996) target three land types ideal for energy crop production, namely lands that are low-yielding, highly erodible, or wetlands that have been converted to farmland. They maintain that "for many hectares of marginal farmland, energy crops could provide a desirable ecological compromise and an economic opportunity (Paine et al., 1996, p. 240)."

It is important to note, however, the less attractive characteristics of energy crops. They are not as financially competitive as other biomass sources, such as residues or wastes (Easterly and Burnham, 1996). Nor are there guarantees that they will be produced sustainably. Nonhebel (2002) found that more intensive farming of ECs (with increased fertilizer and pesticide use) produced greater yields along with reduced energy efficiency compared with extensive farming (less inputs). Higher energy efficiency is more attractive in terms of sustainability and carbon emissions, but higher yields might be more attractive to the grower.

All of the above-mentioned biomass sources are important to a sustainable energy sector, but because energy crops provide a range of socio-economic and environmental benefits and are expected to be the greatest contributor to future biomass feedstock, we have chosen to make them the focus of the current model.

GORCAM

With biomass envisioned for a significant role in future electricity supplies under S.139, we wanted to investigate carbon emissions and capacity from biomass using a system dynamics approach. We used previous work by Schlamadinger et al. (1997) as a basis for our model. They developed GORCAM, an Excel spreadsheet that models several land management scenarios and uses for harvested biomass, as they relate to atmospheric carbon mitigation practices. Land management includes afforestation, conventional forestry, short-rotation forestry/energy crops and the removal of forest and agricultural residues. Once harvested, the biomass can be used in long- or short-lived products as well as for energy. The model simulates the flow of tons of carbon from one stock to another on either a one hectare or 100 hectare basis. These stocks and flows are depicted in Figure 1, where the land management scenarios are represented by the stocks of vegetation, soil and five litter pools (leaf, branch, stem and woody and fine roots). The fate of the biomass is represented on the right side of the diagram. The amount of carbon released to the atmosphere versus that which is sequestered in the other stocks are key outputs of the model. An additional component of the model calculates the reduction in fossil fuel use when biomass is used either in place of fossil fuels for energy, or in place of products that require high energy inputs during manufacturing (such as steel).

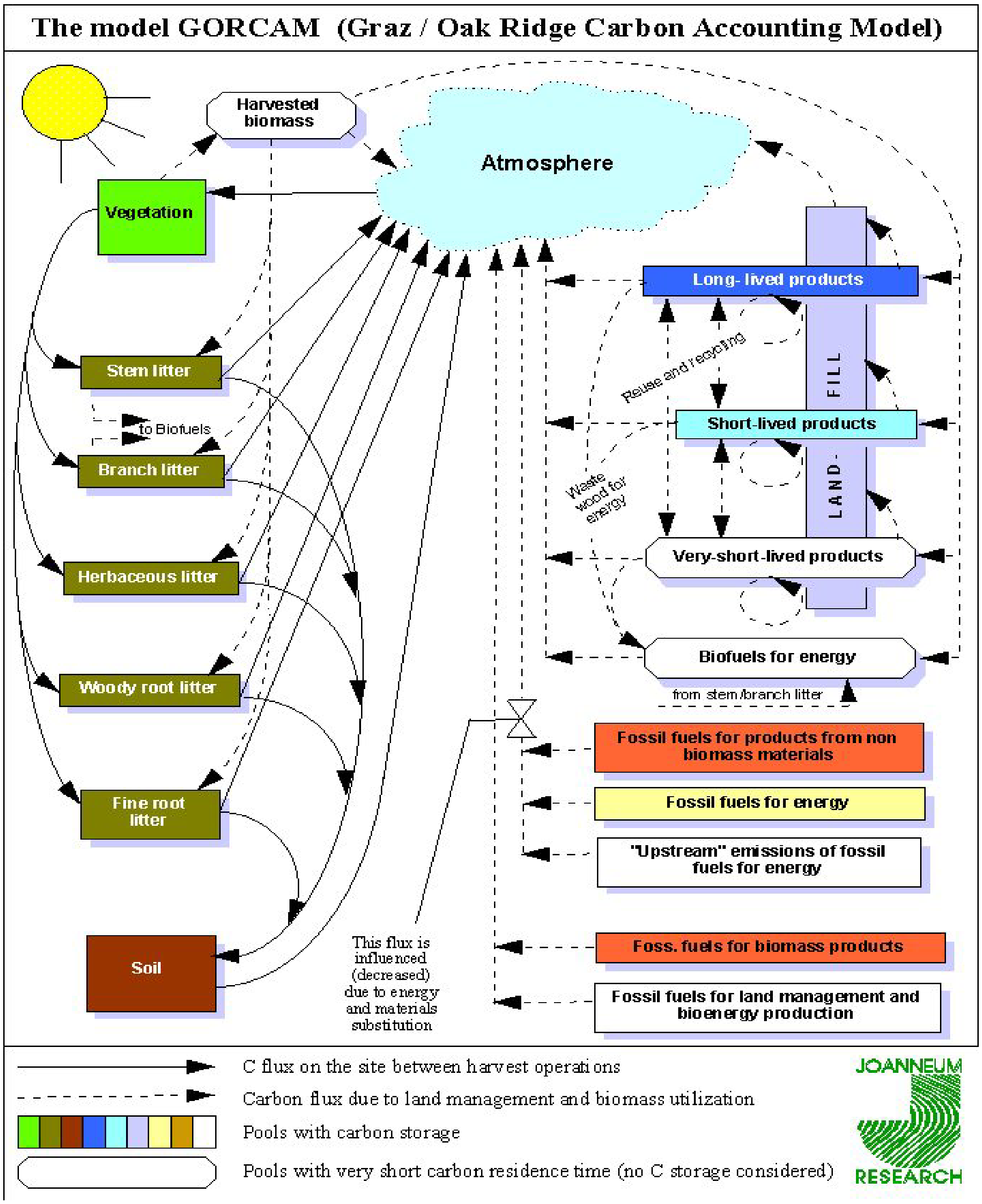

Figure 1. GORCAM flow diagram from http://www.joanneum.ac.at

Four important findings were reported by Schlamadinger et al. (1997) concerning the capability of bioenergy and biomass-based products to reduce carbon emissions. First, short-rotation forestry was more effective at reducing atmospheric carbon, especially when replacing fossil fuel-based energy, due to high growth rates and low energy inputs (i.e. fertilizer, etc). Second, harvested biomass must be processed and used in an efficient manner to make a positive impact. Third, over the long-run, replacement of fossil fuels and non-wood products with biomass will lead to a reduction in carbon released to the atmosphere. Fourth, the amount of carbon stored onsite prior to the implementation of varying land-use strategies did affect carbon stocks and flows. Therefore, assessing the effectiveness of a strategy should take carbon stored onsite into consideration. These results indicate that using biomass to displace fossil fuels is preferred over simply planting trees to sequester carbon.

One GORCAM scenario of particular interest to us was fuelwood plantations dedicated to energy generation. In this scenario, trees grow in an S-shaped pattern until they are harvested in 20-year intervals. Over time, the carbon stored in litter and soil increases slightly (Figure 2).

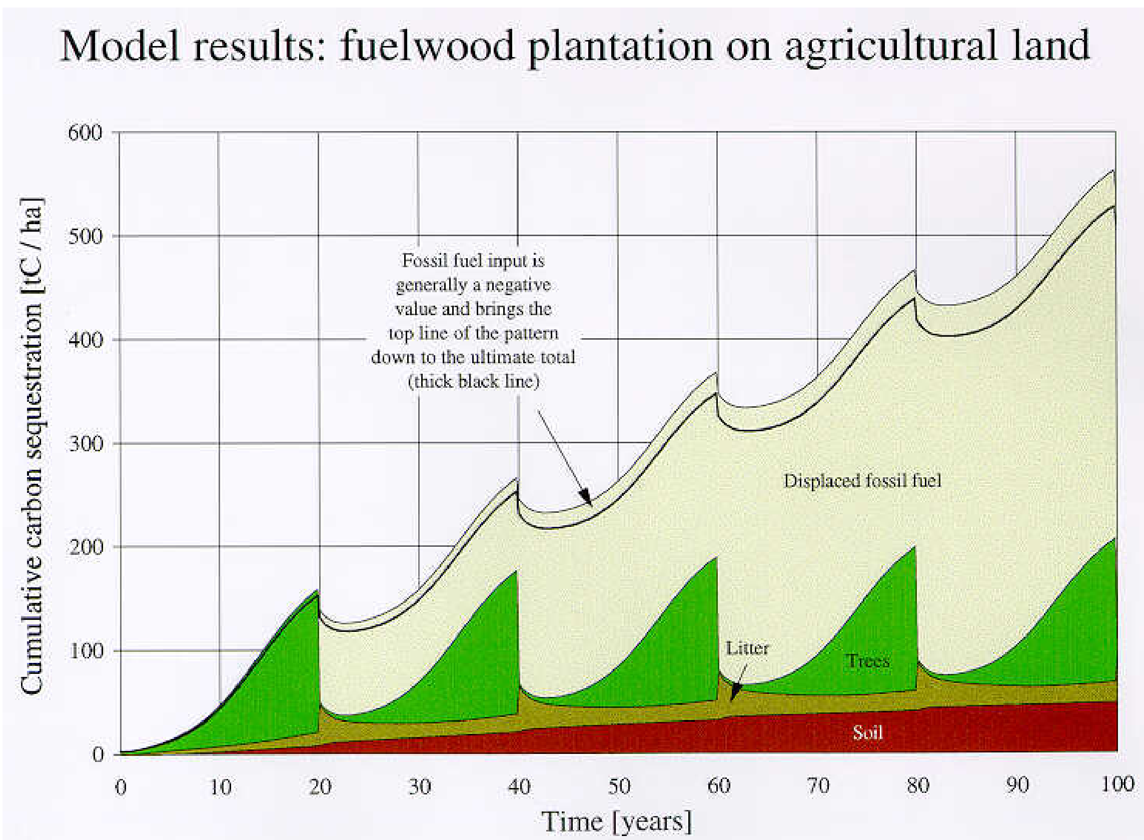

Figure 2. GORCAM output for 20 year fuelwood plantation from http://www.joanneum.ac.at

The soil carbon accumulation is gradual, whereas the litter carbon spikes up after harvest when residues are left behind. It then it smoothes out as the litter decomposes. Our model follows the carbon cycling of biomass production for one hectare of a fuelwood plantation and replicates the output generated by GORCAM. We will show matching results in a subsequent section.

The System Dynamics Method

Our analysis is based on the system dynamics approach pioneered by Forrester (1961) and explained in recent texts by Ford (1999) and Sterman (2000). System dynamics models are normally implemented with visual software to aid in model construction and testing. Stocks and flows are the basic building blocks of system dynamics models, as we illustrate in Figure 3. Figure 3A shows the carbon flows in a simplified model of carbon accumulation in the atmosphere, the vegetation and the litter. Figure 3B shows the same model with highly abbreviated names, names which make it easier for one to write the corresponding differential equations in Figure 3C. System dynamics models are constructed as stock and flow models using visual software, like the Vensim diagram shown in Figure 3A. However, they may be viewed as a coupled set of first order, differential equations, with a separate differential equation for each stock in the model. The differential equations are solved through numerical integration (Ford, 1999, Ch. 11) with the step size set sufficiently small for simulation accuracy.

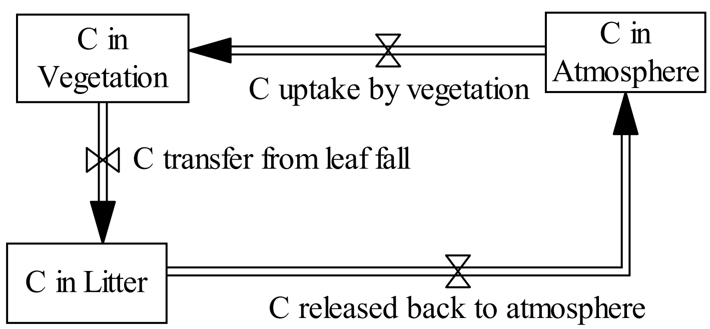

Figure 3A. Example of stocks and flows in a Vensim diagram of carbon cycling.

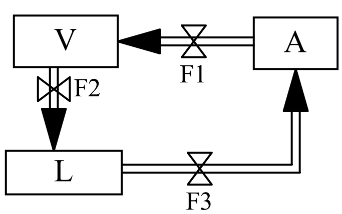

Figure 3B. Same model in Vensim with short names.

DV/dt = F1 – F2

DL/dt = F2 - F3

DA/dt = F3 - F1

Figure 3C. Same model in the form of a set of differential equations.

Figure 3. System dynamics modeling

The first step in construction of system dynamics models is identification of the key stocks. The clarity of the GORCAM documentation (see Figure 1) makes stock identification easy. Each stock is measured in metric tons of carbon (tC), and each of the flows is measured in tC/year. The GORCAM model is documented in quite some detail (Schlamadinger et al., 1997), so it is possible to translate most of the GORCAM algebraic equations into similar Vensim equations, though the equations are difficult to understand at times. The GORCAM calculation of biomass growth is represented in the following equations:

$$\Phi_{A\text{-}V}(t) = g_{init} * \Delta t + \Sigma\Phi_{V\text{-}L}(t) \qquad \text{if } V(t-\Delta t) < V_{max} / 2$$

$$\Phi_{A\text{-}V}(t) = 2*g_{init} * [1-V(t-\Delta t)/V_{max}] * \Delta t + \Sigma\Phi_{V\text{-}L}(t) \qquad \text{if } V(t-\Delta t) \geq V_{max} / 2$$

The general pattern of growth in biomass is "S Shaped Growth." (For example, if the green segment of Figure 2 were allowed to grow without interruption by harvesting, the total tC in the biomass would appear similar to S-shaped or sigmoidal growth. We take a somewhat different approach, as explained by Ford (1999, Chapter 6)). We assume that the stock of biomass is subject to an intrinsic rate of growth when the biomass is small. As the biomass grows toward a user-specified maximum, the growth rate is lowered below the intrinsic growth rate. We assume that the reduction in growth is due to the effect of competition, and we experiment with different parameter values to obtain a good match with the GORCAM results in Figure 2. Stocks and flows are the key building blocks of system dynamics models, but the feedback loops are what give the model its structure. The key loops in our model are the standard set of loops that generate S-shaped growth (see Ford, 1999, Ch. 6).

The WSU Model of Carbon Cycling from Dedicated Energy Crops

We structured our model based on GORCAM in terms of the important stocks: vegetation, litter, soil and atmosphere. The units for the stocks are all in metric tons of carbon and the flows are in tons of carbon per year. The model is run for 100 years with a time step of .0625 years. In contrast to the GORCAM model, we focused strictly on fuelwood plantations planted for power and thus did not include products derived from the wood. We used the same parcel size as GORCAM, one hectare. The stocks are prominently displayed with different colors representing each of the different pools of carbon. The system is composed of several screens that are interconnected. Each screen shows a view of each of the major components of the model which we will explain in more detail below. Each view is linked to all of the other views via a "Go to" box. These boxes are also color coded and simply clicking on them when the model is in "locked mode" will bring you to that view. Two output graph screens are also accessible via these boxes. One shows the carbon sequestered in the vegetation, litter and soil. The other shows the carbon impacts when biomass is used to replace a coal plant.

Vegetation Carbon

The vegetation view is shown in Figure 4. This represents the carbon dynamics of the standing stock of the EC. The uptake of carbon is dependent on the intrinsic growth rate of the species and is impeded by competition among plants as the plant density of the area increases. The *annual C assimilation rate* by the vegetation is the *intrinsic growth rate* multiplied by the *assimilation rate multiplier from density*.

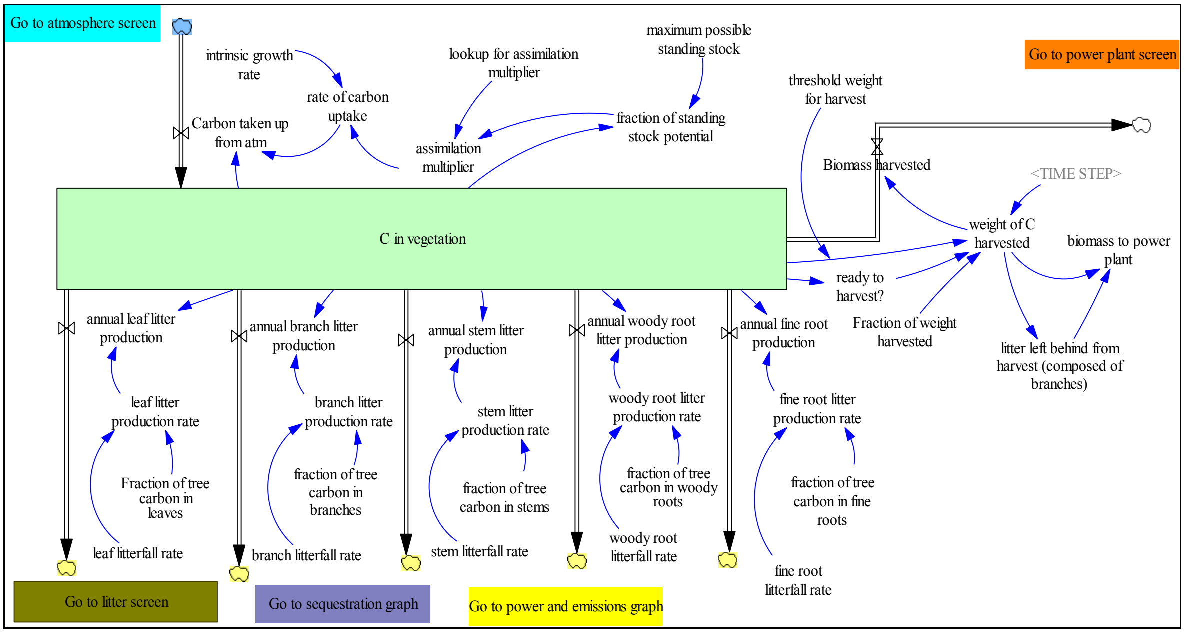

Figure 4. Vegetation view

Litter production from five plant parts (stem, leaf, branch, woody roots and fine roots) occurs continually. These plant part categories were identified by Dewar (1991) and implemented in the GORCAM model, however, for this model values from work by Lodhiyal et al. (1995) were used with similar results. Each plant part has a corresponding litter production rate and comprises a fraction of the total weight of the standing crop. For example, *leaf litterfall rate* is 1 yr^{-1}, meaning 100% of the leaf biomass winds up in leaf litter each year. The *fraction of tree carbon in leaves* was set to .081 based on an estimate by Lodhiyal et al. (1995), meaning 8.1% of the tree is in the form of leaves. *Leaf litter production rate* is the product of these two variables, which in this example equals .081 yr^{-1}. We do not simulate leaves dropping at a single point in time. Instead, we know that the leaves will fall at some point and this represents 8.3% of the total weight of the vegetation, so the *annual leaf litter production* is *leaf litter production rate x C in vegetation = .081 x C in vegetation.* This same format was used for all five plant parts.

Biomass is harvested at a *threshold weight for harvest* that can be manipulated by the user. If the *C in vegetation* equals the *threshold weight for harvest*, then *ready to harvest* = 1, if not, *ready to harvest* = 0. When *ready to harvest* = 1, the flow of biomass out of the standing stock can proceed. The entire stock of biomass is not sent to the power plant for two reasons. First, not all of it is actually harvested. The *fraction of weight harvested* is 85%, indicating a system where a small portion of the tree stem is left to regenerate another crop. This method of crop management is called coppicing, and is used with willow and poplar crops. Second, not all of the biomass is collected once harvested, some remains on the field afterwards. The fraction of weight that goes to the power plant is 80%, based on an estimate by Marland and Schlamadinger (1995). The *biomass left behind from harvest* is primarily branches, thus it was allocated to the branch litter stock.

Litter and Soil Carbon

The total amount of carbon flowing into the litter layer is a combination of natural litterfall in addition to litter left behind after harvest (Figure 5).

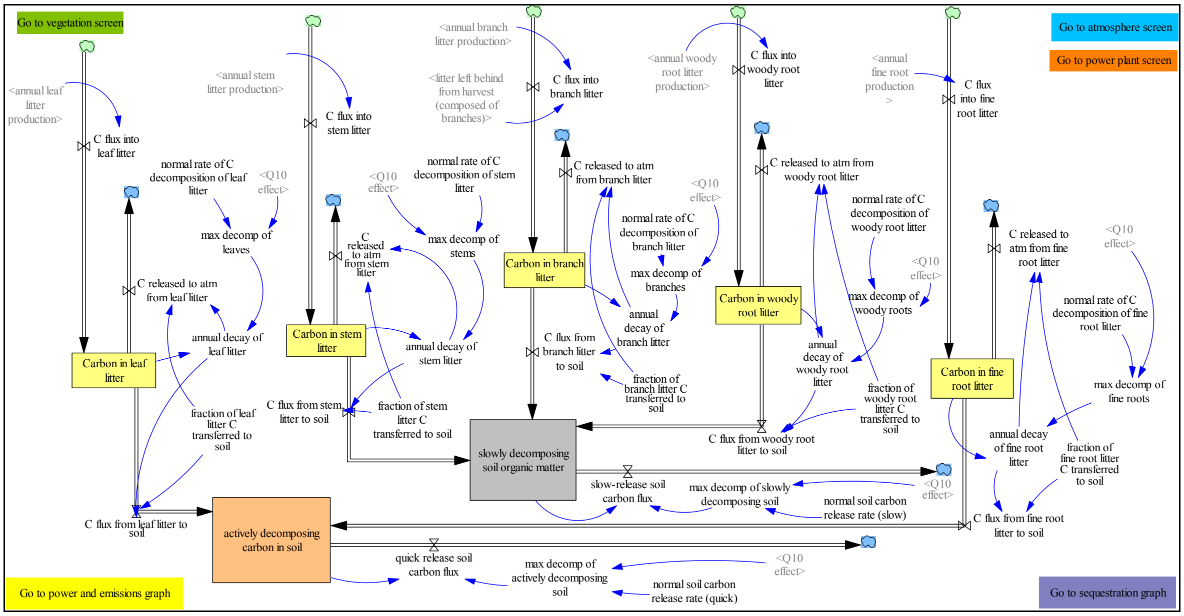

Figure 5. Litter and soil carbon view

The litter produced each year can follow one of two paths. It can decompose, releasing carbon directly to the atmosphere, or it can be incorporated into the soil. There are two soil stocks, one for actively decomposing organic matter and one for slowly decomposing matter. Dewar (1991) estimated the fraction of litter from each plant part that becomes part of the soil. For the leaf litter, the *fraction of leaf litter C transferred to the soil* is .5 yr^{-1}, or 50% yr^{-1}. Obviously, then the *C released to the atm from leaf litter* is also .5 yr^{-1}, but the equation is 1- *fraction of leaf litter C transferred to the soil* since not all litter types follow the same path distribution. To find exactly how much carbon these flows carry out of the stock, we included a variable for the *annual decay (of leaf litter, etc).* This is the product of the *carbon in (leaf) litter* and the *maximum decomp of (leaves)*. Each year 85% of the leaf litter breaks down and either flows to the atmosphere or is incorporated into the soil (Dewar, 1991). Fine roots also breakdown at this rate, but the woodier plant parts take much longer to decompose. Therefore, the fine root litter and leaf litter flow to the active soil and the litter from woody plant parts flows to the slowly decomposing soil.

The *slow-release soil carbon flux* is simply the *maximum decomp of slowly decomposing soil x* of the total stock of *slowly decomposing soil organic matter* per year. The *normal soil carbon release rate (slow)* is.015 yr^{-1} or 1.5% per year. The *quick-release soil carbon flux* is simply the *maximum decomp of actively decomposing soil x* of the total stock of *actively decomposing soil organic matter* per year. The *normal soil carbon release rate (quick)* is .8 yr^{-1} or 80% per year. This approach was different than GORCAM, which has only one soil carbon pool with a 1.5% release rate used by Dewar (1991). We were, however, able to replicate the GORCAM results. During the simulation period of 100 years the soil continues to accumulate soil. However, if a longer time horizon is simulated the soil carbon reaches equilibrium.

Atmospheric carbon

The atmosphere view acts as the carbon accounting component of the model (Figure 6). It keeps track of the carbon released into the air as well as that which is taken up by the growing vegetation. Three flows enter the stock. The first is the carbon released from decomposing litter and soil stocks. The second is the net carbon released during electricity generation. If this flow only accounted for biomass burning, we would expect the atmospheric carbon to decrease slowly over time as carbon accumulates in the soil and litter. The last flow is the carbon released during the production and transportation of the feedstock as well as the carbon released during the power plant construction. The energy used in crop production is of great concern to people who are aware of the high energy inputs of typical agricultural crops. A life cycle assessment of a gasification system using dried wood chips, however, found that the when poplars are used, the total carbon released by the system in excess of what is removed by the next crop is only 5% (Mann and Spath, 1997). This is a small percentage, but is included nonetheless to address energy-input concerns.

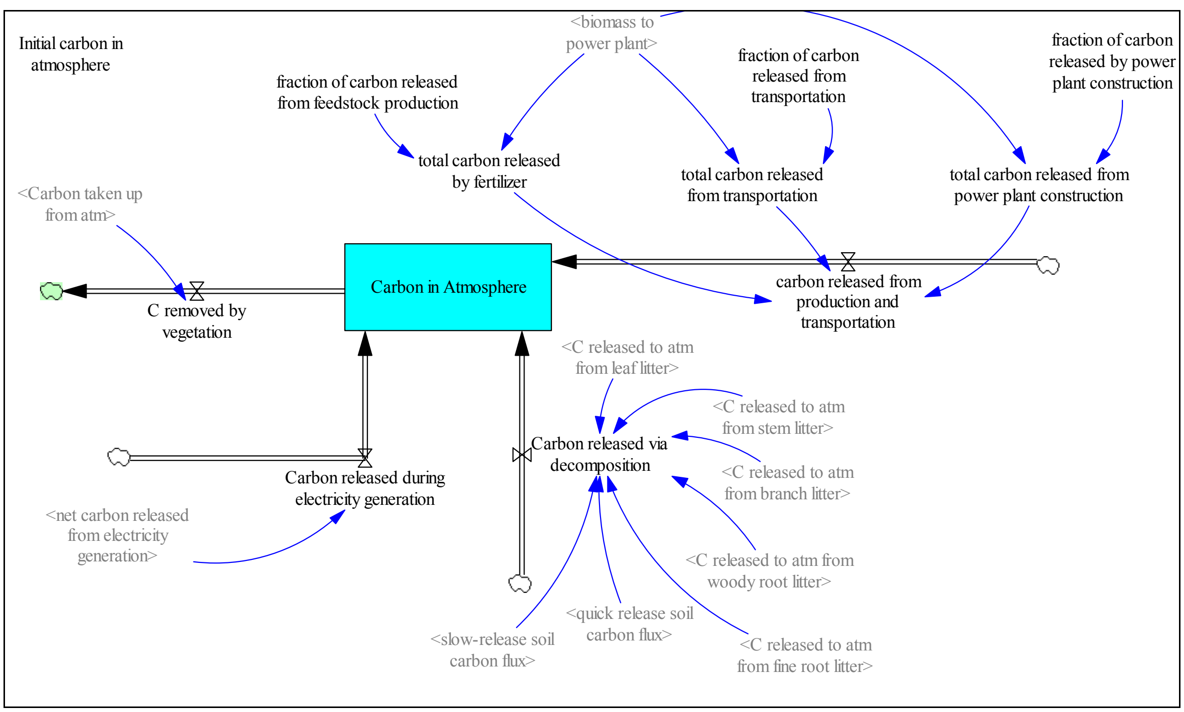

Figure 6. Atmosphere view

The initial value for the atmosphere stock was arbitrarily set at 500 tons of carbon. This serves as a starting point for comparison to the other carbon pools. A graph of carbon in the atmosphere will be shown with our poplar model to follow.

Power plants

The biomass harvested in the vegetation view is then sent to the power plant (Figure 7). Some of the biomass that is harvested is lost in transit, but this has already been accounted for in the *fraction of weight that goes to the power plant* found in the vegetation view. Therefore, it is assumed that all of the carbon in the harvested crop that arrives at the power plant is released into the atmosphere upon combustion, meaning the *total tons of carbon emitted by biomass burning* is the same amount as the *biomass to power plant.* Biomass is dried prior to combustion, with a resulting carbon content of 50.88% (Mann and Spath, 1997). The *dry tons of wood per ton carbon* is therefore 1.97 tons dry wood/tC. One pound of fuelwood produces 8600 BTUs (Haq, 2002).

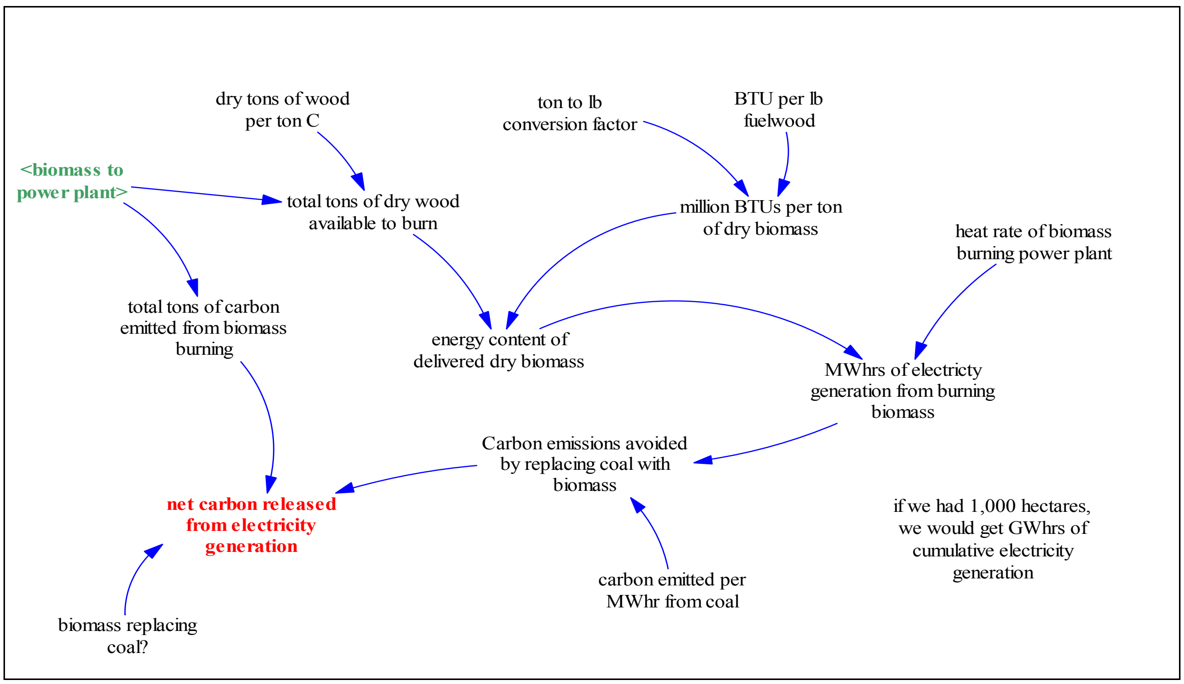

Figure 7. Power plant view

From here we calculate the *energy content of delivered dry biomass.* This multiplied by 1000 and divided by the heat rate (a typical heat rate for a biomass-burning power plant is 14,000 BTU/kwh (www.westbioenergy.org)) gives us the total *MWhrs of electricity generation from burning biomass*. Assuming coal releases 200lbs of CO_2 per 10^6 BTUs, and a heat rate of 10,000BTU/kwh for coal plants, the *carbon emitted per MWhr from coal* is .245 tC/MWh. We found that approximately one thousand hectares of poplars can fuel a 1MW power plant. We created a hypothetical scenario where the biomass replaces the coal burned in a 1MW power plant. Thus the *carbon emissions avoided by replacing coal with biomass* is simply the *MWhr of electricity* *generation from burning biomass * carbon emitted per MWh from coal.* When this amount is subtracted from the carbon from biomass burning, we find the *net carbon released to the atmosphere from electricity generation*.

Model Parameters

Table 3. Vegetation parameters

Variable name	Value (s)	Units	Comments
intrinsic growth rate	.165 (20yr fuelwood) *Or* 0.36 (poplars)	yr^{-1}	a reasonable growth rate that gave results that matched the GORCAM results for 20 yr rotation a reasonable growth rate for poplars that provides a 6tC/year uptake at the steepest point in a growth curve. (6tC average uptake by poplars is given by Schlamadinger *et al.*, 1997)
maximum standing stock of biomass	400 *Or* 100	tC	Assuming s-shaped growth, with harvest occurring when the growth rate begins to decrease (at around 160 tC for 20yr and 42tC for poplars)
leaf litterfall rate	1	yr^{-1}	All of the leaves of a poplar tree fall within the year
fraction of tree carbon in leaves	0.081	dmnl	Lodhiya *et al.*, 1995 (the average of 5-yr and 8-yr old trees was used for each parameter)
branch litterfall rate	0.004	yr^{-1}	" "
fraction of tree carbon in branches	0.143	dmnl	" "
stem litterfall rate	0.004	yr^{-1}	" "
fraction of tree carbon in stems	0.576	dmnl	" "
woody root litterfall rate	0.048	yr^{-1}	" "
fraction of tree in woody roots	0.19	dmnl	" "
fine root litterfall rate	0.048	yr^{-1}	" "
fraction of tree carbon in fine roots	0.011	dmnl	" "
threshold weight for harvest	160	tC	Schlamadinger *et al.*, 1997
fraction of weight harvested	0.85	yr^{-1}	Marland and Schlamadinger, 1995
fraction of weight that goes to power plant	0.8	yr^{-1}	Marland and Schlamadinger, 1995

Table 4. Soil and litter parameters

Variable name	Value	Units	Comments
fraction of leaf litter C transferred to soil	0.5	dmnl	Dewar, 1991, p. 248
rate of C decomposition of leaf litter	0.85	yr^{-1}	" "
fraction of stem litter C transferred to soil	0.2	dmnl	" "
rate of C decomposition of stem litter	0.01	yr^{-1}	" "
fraction of branch litter C transferred to soil	0.2	dmnl	" "
rate of C decomposition of branch litter	0.05	yr^{-1}	" "
fraction of woody root litter C transferred to soil	0.5	dmnl	" "
rate of C decomposition of woody root litter	0.1	yr^{-1}	" "
fraction of fine root litter C transferred to soil	0.5	dmnl	" "
rate of C decomposition of fine root litter	0.85	yr^{-1}	" "
Slowly decomposing soil organic matter	.015	yr^{-1}	" "
Actively decomposing soil organic matter	0.8	yr^{-1}	Leaves and fine roots decompose much more rapidly than woody litter

Table 5. Power plant parameters

Variable name	Value	Units	Comments
ton to lb conversion factor	2200	lbs/ton	
BTU per lb fuelwood	8600	BTU/lb	Haq, 2002, p.17
heat rate of a wood burning power plant	14000	BTU/kwh	westbioenergy.com
dry tons of wood per ton C	1.97	t/tC	Mann and Spath, 1997, p. 17
Carbon emitted per MWh from coal	0.245	tC/MWh	Used in the WSU WECC model (not yet published)

Table 6: Atmosphere Parameters

Variable name	Value	Units	Comments
Initial carbon in atmosphere	500	tons	Arbitrary starting value
Fraction of carbon released from feedstock production	.0315	dmnl	Mann and Spath 1997, p. 49
Fraction of carbon released from transportation	.0067	dmnl	Mann and Spath 1997, p. 49
Fraction of carbon released from power plant construction	.0135	dmnl	Mann and Spath 1997, p. 49

The nine stocks are initiated at a value of zero tons of carbon except for the vegetation and atmosphere stocks. The vegetation carbon is 30 tons at the start of the GORCAM simulation and 5 tons in the poplar simulations. For the atmospheric carbon stock, we choose a starting value of 500 tons of carbon, an arbitrary starting value. Tables 3 through 6 show the values for each of the constants in the model. The literature source of the value, or a comment on why the value was chosen, along with the units, is given for each variable. All units are based on a one-hectare plot of land.

The model equations are all simple algebra – multiply, divide, add or subtract. But there is one nonlinear relationship in the model, and for this we use Vensim's lookup table. The nonlinear relationship between the fraction of the land occupied by the crop and the assimilation rate of the crop is in the vegetation view. To account for this restriction in growth a multiplier is generated by a lookup table (Figure 8).

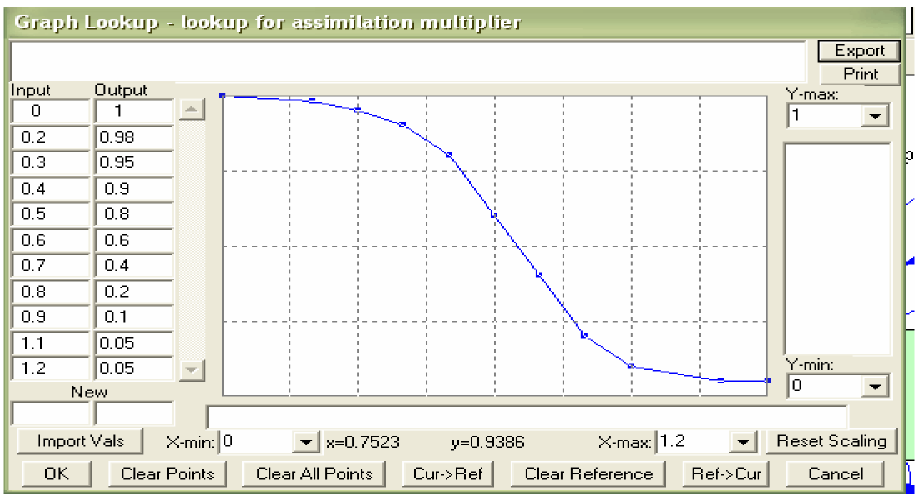

Figure 8. Lookup table for assimilation multiplier

The X-axis is the fraction of the hectare occupied by the crop (i.e., the *C in vegetation / maximum possible standing stock*) and the Y-axis is the multiplier value. When the fraction of the hectare occupied by the crop (the *fraction of standing stock potential* variable in the model) is 0, the *assimilation multiplier* is 1, meaning there is no restriction on the growth of the trees. That is, they grow at the intrinsic rate of 16.5% yr^{-1} (or 36% yr^{-1} for poplar simulations). We assumed that there would always be some assimilation possible, even when the occupied area exceeds what would be considered the maximum possible biomass (set at 400tC/ha to match GORCAM or 100tC/ha for the poplar simulations). Therefore, the assimilation multiplier never reaches 0.

Verification of Simulated Behavior with GORCAM

Figure 2 showed the GORCAM results for a fuelwood plantation harvested every 20 years. Our model shows a close match with the GORCAM results over 100 years (Figure 9). The light grey area shows the carbon sequestered by the crop, the dark grey area represents the litter carbon content and the soil carbon is shown in black. At each harvest the amount of carbon in the standing crop drops as it is removed from the land and transported to the power plant. Over time, the soil carbon increases slightly. The harvest rotation can be changed by increasing or decreasing the threshold weight for harvest. In this scenario, the threshold weight for harvest is 160 tons of carbon (tC). This stacked graph shows the same pattern as the GORCAM model where s-shaped growth brings the vegetation up to about 160 tC before harvest. The litter pattern is also similar to GORCAM, in that it spikes at harvest when some of the harvest is left on the ground, but then the litter decomposes releasing some carbon to the soil and some to the atmosphere.

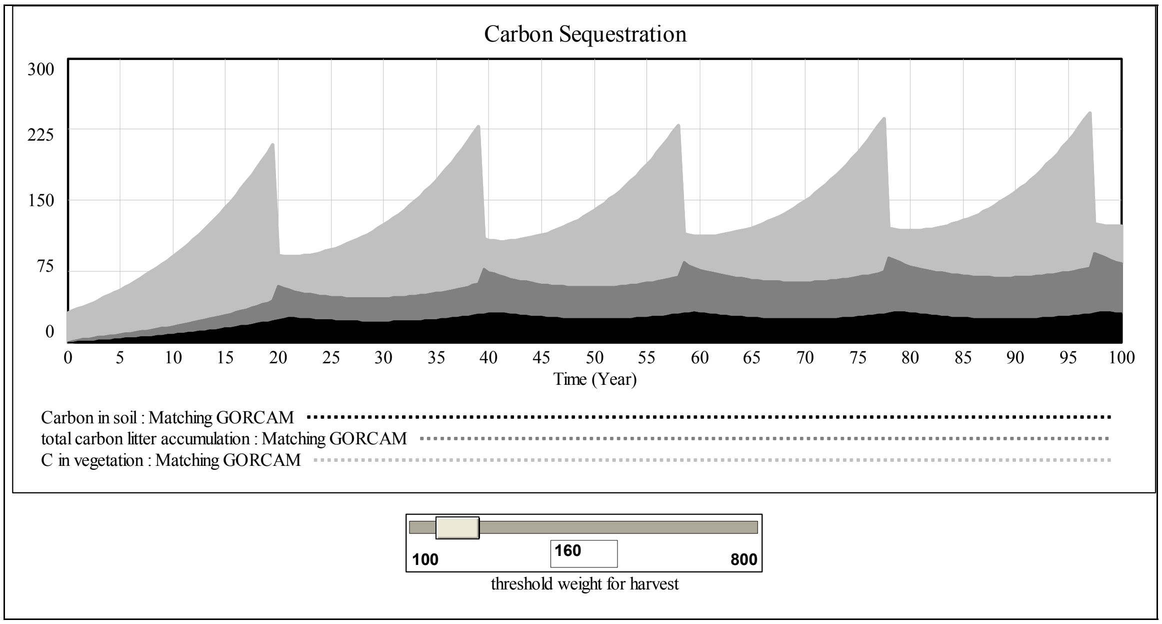

Figure 9. Stacked graph of carbon sequestered by vegetation, litter and soil stocks

The soil carbon also increases, but it reaches an equilibrium state where the carbon entering the stock matches that which is release to the atmosphere. This is slightly different than the GORCAM results where soil carbon continues growing for the duration of the simulation. The fossil fuel use was not included in this graph, but will be addressed in later simulations.

The litter accumulation appears to be higher in our model, possibly due to different parameter values than were used in GORCAM. We have included in our model a user-defined harvest threshold. Vensim has an interactive mode that employs sliders to change variables. The output is instantaneously displayed for the entire simulation period with each move of the slider. The slider in Figure 9 gives a range of harvest thresholds from 100tC to 800tC. This feature becomes important because it allows the user to define the number of years for the harvest rotation.

Simulating Poplars as a Fast Growing Energy Crop

The species chosen for energy crop production will depend on the site characteristics. As previously mentioned, herbaceous crops such as switchgrass and woody crops such as poplars have been identified as having high potential as energy crops, if they are grown in a suitable environment. In the U.S., switchgrass will do best in the southern and southeastern parts of the country, while hybrid poplars could be grown in the northeast, northwest and Midwest (Easterly and Burnham, 1996). Poplars therefore have a significant range in which they can be grown. This is one of the reasons why we chose to look at poplars. Another reason is the plethora of information on poplar energy crops and various models focused on poplar production, including GORCAM. In GORCAM the poplars grow at a rate of 6tC/ha/year. Our model uses a growth rate of 36% per year, which amounts to 6tC per year during the linear phase of s-shaped growth. The threshold weight for harvest can be changed to simulate various rotation periods. The output for carbon sequestration in the vegetation, litter and soil stocks is shown in Figure 10.

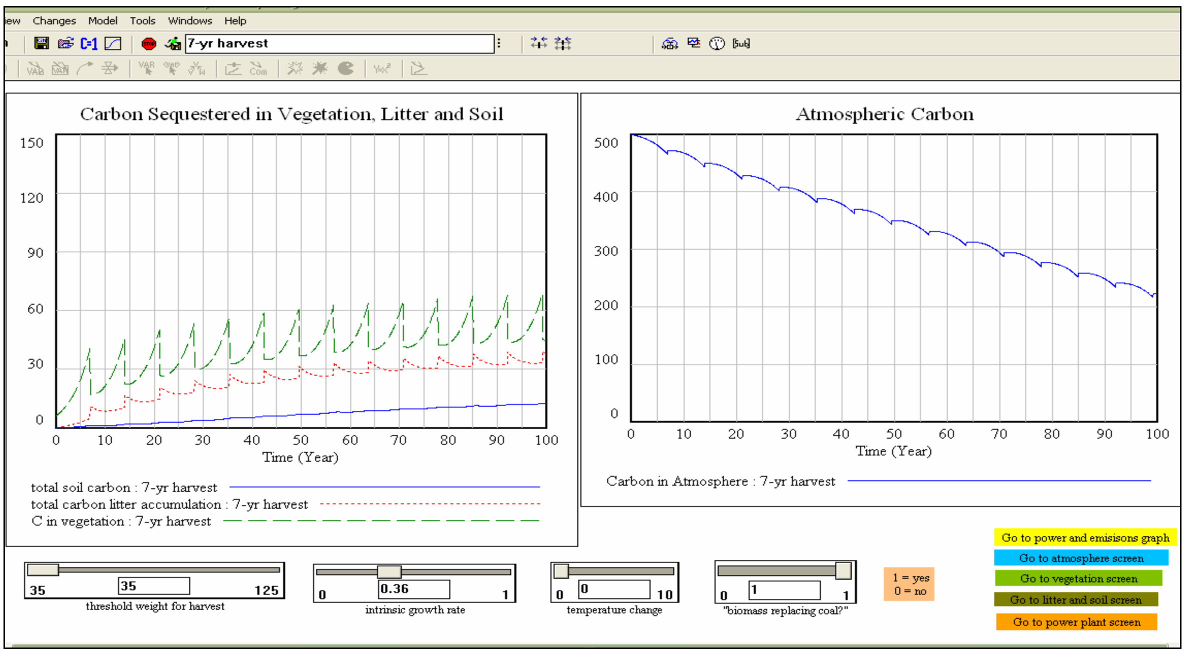

Figure 10. Poplar crop with 7 year harvest rotation

Here we have simulated a harvesting rotation of approximately 7 years. We accomplished this by calculating how much standing stock would be on site after 7 years and then setting the harvest threshold to that amount (in this case 35 tC per hectare). The carbon in the atmosphere is represented in the graph on the right in Figure 10, which starts at 500 tC. The energy crop is being used exclusively for energy production and we have modeled a replacement of fossil fuels from one hectare of trees. By doing this the carbon in the atmosphere is reduced because trees are being planted and taking up carbon while at the same time no more carbon is being released into the atmosphere from fossil fuel burning.

Figure 11 represents a no-harvest scenario that might be found when trees are planted specifically for carbon sequestration. In this case, the carbon in the atmosphere is not reduced as much as the previous scenario. This result agrees with work by Marland and Marland (1992) who reported that fast-growing crops would have more climate change mitigation benefits if they were for energy generation rather than strictly for carbon sequestration.

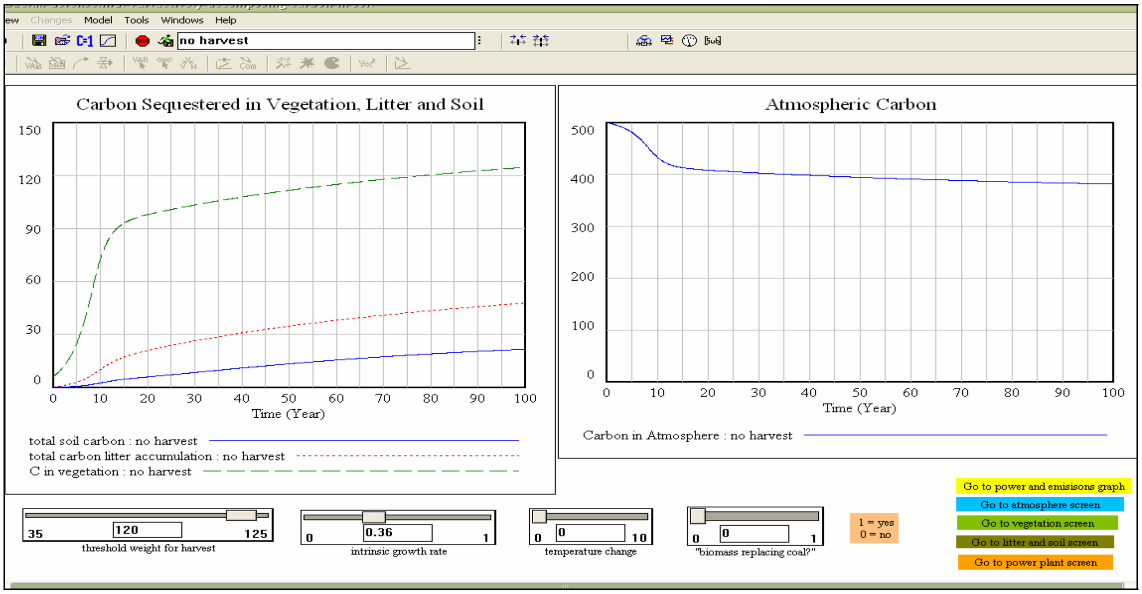

Figure 11. Poplar crop that is not harvested, i.e., planted solely for carbon sequestration

The following two figures illustrate that an increase in harvest interval will sequester more carbon from the atmosphere as the carbon is incorporated into the soil and litter pools and as the biomass replaces fossil fuels (Figures 12 and 13).

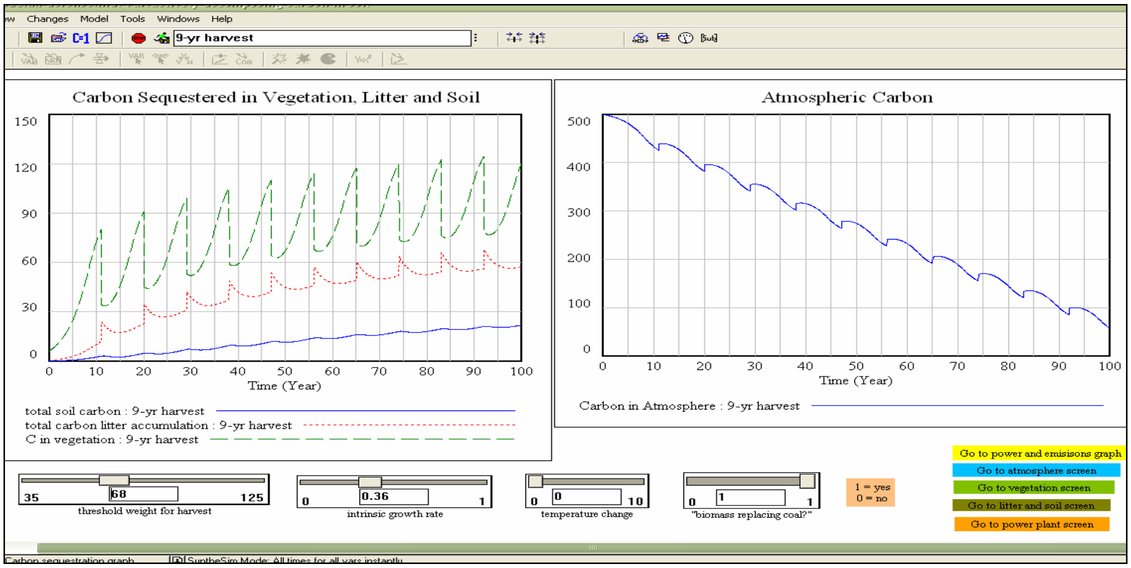

Figure 12. Poplar crop with 9-year harvest rotation

In the first scenario, the harvest interval is approximately 9 years. As the trees grow to be quite large, competition among trees is begins to inhibit growth. The assimilation multiplier in the model imposes this inhibition.

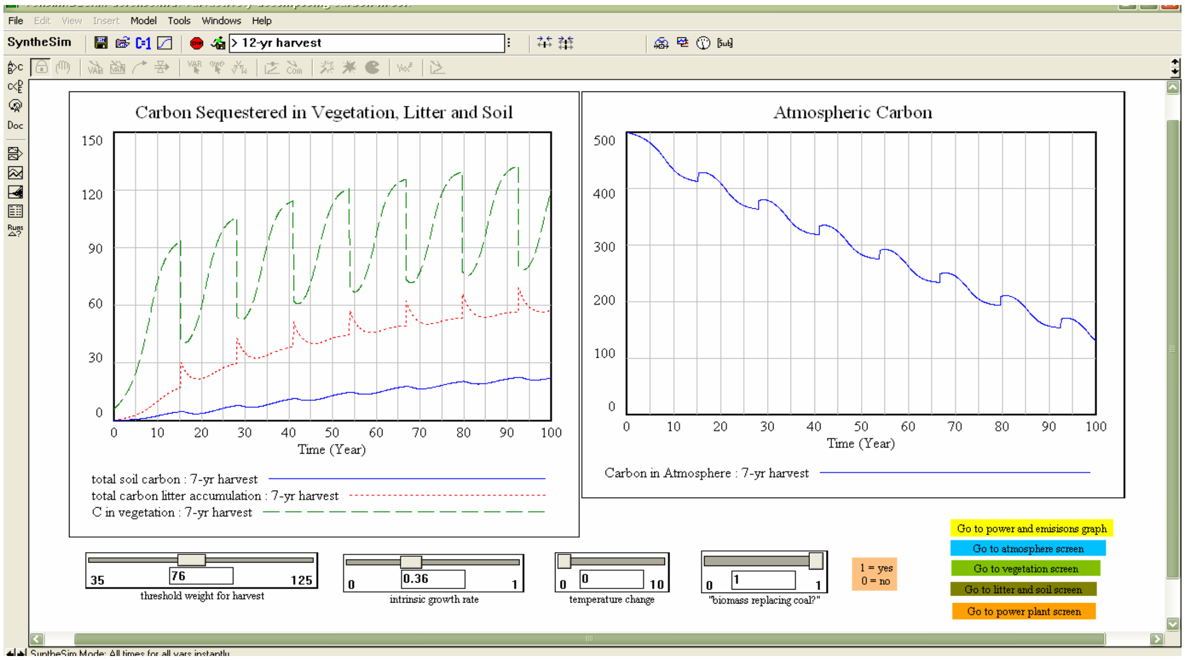

Figure 13. Poplar crop with greater than 12-year harvest rotation

Harvesting at an interval greater than 9 years begins to reduce the effectiveness of ECs to draw carbon out of the atmosphere (Figure 13). A comparison of the right-hand graphs of carbon in the atmosphere from Figures 12 and 13 shows that the 9-year rotation has a steeper slope and more carbon removal than the scenario with a harvest interval slightly longer than 12 years. It appears that 9 years is the turning point in carbon benefits from growing dedicated energy crops for electricity production.

Size of the Power Plant

Figure 14 shows the remainder of the electricity generation view. The model accumulates the electricity generated by burning the wood in a biomass plant. The generation might occur every 9 years, and we simply add up the generation over the 100 year simulation. The stock applies to 1 hectare of land – the amount used by the original GORCAM. If we had 1,000 hectares of land, we would accumulate GWhrs of electricity generation. Then, for purposes of comparison, the model accumulates the electricity generation from continuous operation of a hypothetical power plant. We can jump to another screen to experiment with the size of the power plant.

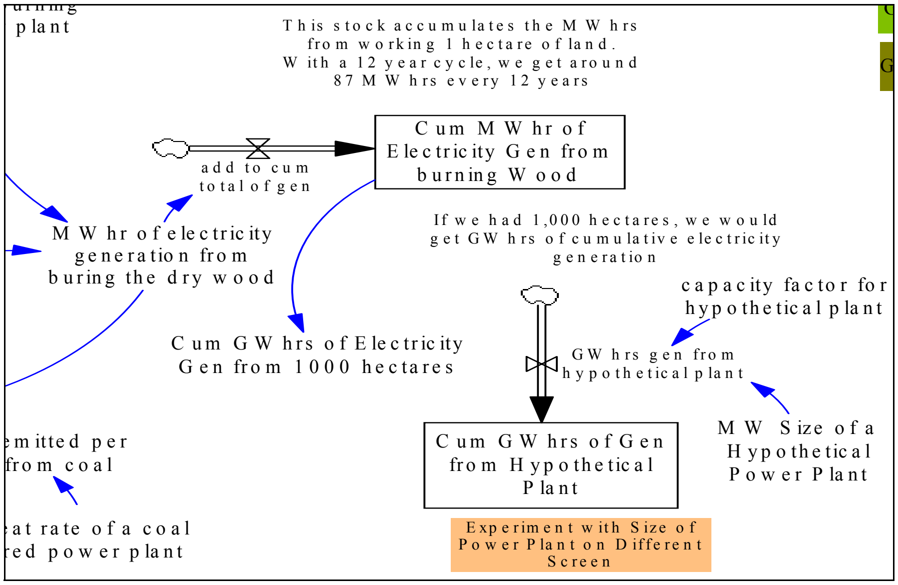

Figure 14. The power plant size that could be supported by biomass

Figure 15 shows a match of cumulative electricity generation if we set the size of the hypothetical power plant to 1.276 MW. The red line shows continuous growth in power generation from the power plant that runs 80% of the hours in a year, year after year. A 1.276 MW plant would produce 80% times 8760 hours per year which turns out to be nine GWhrs per year. After 100 years, the total will grow to around 900 GWhrs, as shown in Figure 15.

We get approximately the same result from the 1,000 hectares of poplars. There are fourteen crops harvested during the 100 years. Each crop will produce 64 MWhrs of electricity. When we scale up to 1,000 hectares, each crop produces 64 GWhrs of electricity. When this happens fourteen times, we have about 900 GWhrs of electricity --- approximately the same result as the 1.276 MW power plant.

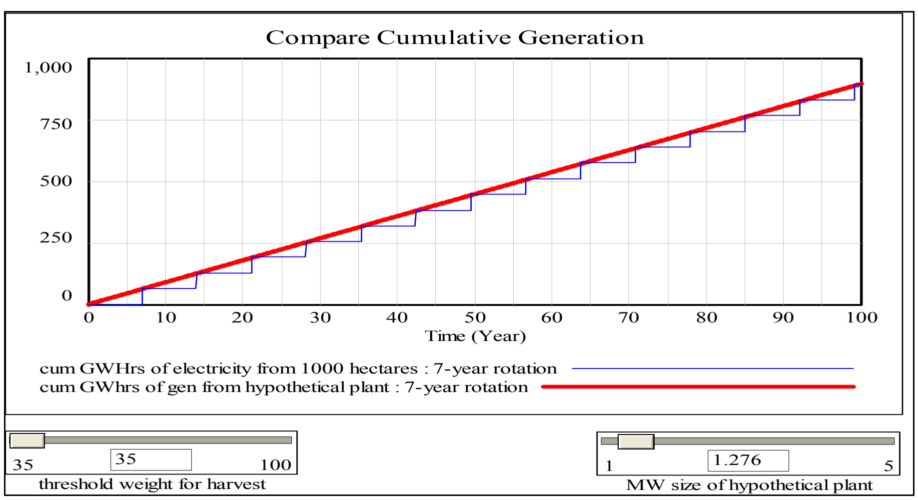

Figure 15. Experimenting with the size of the hypothetical power plant to match cumulative electricity generation from 1,000 hectares of poplars.

Conclusion

The Climate Stewardship Act calls for emissions trading between entities required to comply with the program. It has yet to be decided how biomass power plants will be treated under such a scenario, but in other renewable energy programs, such as Renewable Portfolio Standards, biomass reaps the benefits of being considered a renewable resource. Biomass generators not only earn money on the power they produce, but they also earn money on TGCs that utilities buy from them to meet their RPS requirement. The proposal for S.139 includes a provision for a limited number of offset credits for projects that sequester carbon. If there was a way for biomass producers to show net carbon sequestration from their activities (due to carbon accumulation in the soil), it is conceivable that they might qualify for these credits.

Results from our model indicate that a rotation interval of around 9-years produced optimal carbon benefits. Harvesting on shorter rotations did not allow for as much carbon to be sequestered in the soil and litter stocks. Harvest intervals longer than 9-years lead to competition between trees, which then reduces the carbon benefits. Furthermore, the benefits of using poplars for electricity generation will be much greater than just planting for carbon sequestration.

Under S139, large investments in biomass energy generation are expected to be made. Future work will address the ability of dedicated energy crops to keep up with the demand of the newly built biomass power plants, as well as the land requirements of such a system.

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