Carbon Cycling in Forests: Simple Simulation Models

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Introduction

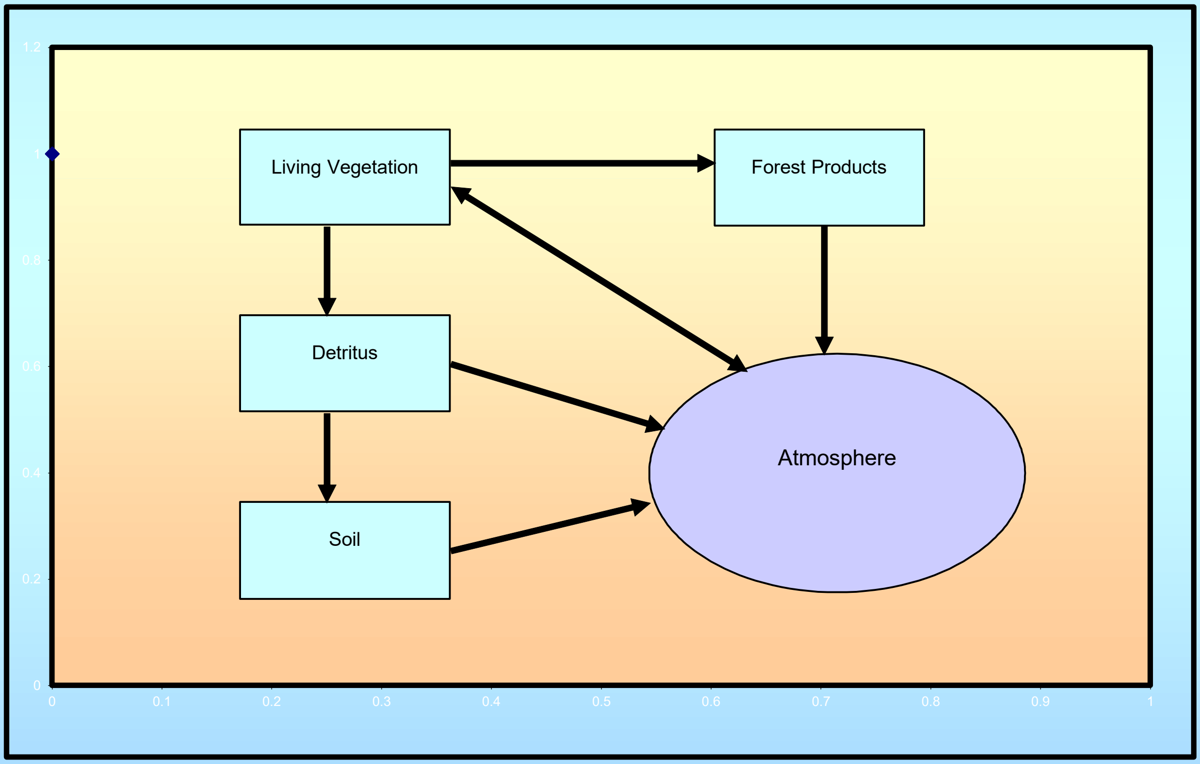
This document describes a series of simple models that allows one to explore the basic factors controlling the sequestration of carbon by forests. The models are programmed in Excel and represent the key relationships determining the amount of carbon sequestered by a forest. Each model explores a different aspect of the carbon sequestration problem. The user is encouraged to use the models to explore the consequences of changing growth and decomposition rates, the interval between disturbances, the level of forest harvest, and the efficiency of forest products manufacturing.

The Basic Model

There are four components that need to be considered in the carbon cycle of forests. They are:

1. The living vegetation (mostly trees),
2. Detritus (partially decomposed leaves, branches, roots, and boles),
3. The soil (well decomposed organic matter, mostly in the mineral soil), and
4. Forest products (Figure 1).

Figure 1. Key pools and flows of carbon in a forest ecosystem.



The models are structured to simulate a disturbance that kills all the vegetation. Depending on the parameters that are used, the disturbance can remove some or all of the detritus. Other pools such as soil carbon and forest products are assumed not to be influenced by disturbances. Carbon flows from live trees to detritus (because of mortality) and forest products (because of timber harvest). Carbon also flows from detritus to soil to simulate the effects of extensive decomposition.

Calculations

Living vegetation carbon stores are modeled using a Chapman-Richards function:

$$L_t = L_{max} (1\text{-exp } [B_1 * t])^{B_2}$$

where L_t is the live vegetation carbon store as time t, L_{max} is the maximum carbon store of live vegetation possible (a function of site productivity), B_1 is a parameter that determines the time required to approach the maximum store, and B_2 is a parameter that determines the lag in vegetation growth after disturbance (Cooper 1983). Whenever a disturbance occurs time is reset to 0 so that live biomass will decrease to 0 as well.

Detritus is simulated as one pool with an average decomposition rate, a loss from fire, and inputs from normal mortality as well as that associated with major disturbances:

$$D_t = D_{t-1} + M_t + DM_t - K_t - F_t - SF_t$$

Where D_t is the store of carbon in detritus at time t, D_{t-1} is the same but for the previous year, M_t is the input from mortality associated with competition and minor disturbances, DM_t is the mortality associated with major disturbances (timber harvest, fire, wind), K_t is the loss from decomposition in year t, F_t is the loss from fire in year t, and SF_t is the loss to soil formation in year t. The first type of mortality inputs are calculated as:

$$M_t = m * L_t$$

Where m is the mortality rate-constant. The mortality inputs associated with major disturbances are calculated as:

$$DM_t = (1-h) * L_t$$

Where h is the fraction of live vegetation that is removed by harvest. Losses from decomposition are calculated as:

$$K_t = k * D_{t-1}$$

Where k is the decomposition rate-constant (the average for all types of detritus). Losses from fire are calculated as:

$$F_t = f * D_{t-1}$$

Where f is the fraction of detritus that is removed by fire. The loss of detritus to soil formation is:

$SF_t = sf * D_{t-1}$

where sf is the soil formation rate. Soil carbon stores (S_t) are controlled by inputs from detritus and losses via decomposition:

$S_t = S_{t-1} + SF_t - KS_t$

Where S_{t-1} is the soil store the year before t and KS_t is the decomposition loss from soil as determined by:

$KS_t = ks * S_{t-1}$

Where ks is the rate-constant describing soil carbon decomposition.

Forest products are input from living vegetation periodically by harvest. The amount of harvest that ends up in forest products after manufacturing is variable, as is the longevity of the products themselves. Only one aggregated pool of forest products is considered:

$P_t=P_t-1 + MF_t - PK_t$

where P_t is the forest products store as year t, P_{t-1} is the same for the previous year MF_t is the input from manufacturing and PK_t is the loss from decomposition, incineration, and other mechanisms that release forest products to the atmosphere. The input from manufacturing is computed as a fraction of the harvested carbon:

$MF_t = mf * h * L_t$

Where mf is the manufacturing efficiency expressed as a fraction of the harvest turned into long-term forest products, h is the fraction of live carbon harvested, and L_t is the live carbon store the year of the harvest. The loss of products from decomposition, incineration, etc is calculated as:

$PK_t = pk * P_t$

where pk is the rate-constant for loss of forest products.

The total carbon stores at time t are calculated as:

$T_t = L_t + D_t + S_t + P_t$

where the stores are defined as above. The flux in carbon stores (or net change) is calculated as:

$\Delta T_t=T_t - T_{t-1}$

Where T_t is the total store at time t and T_{t-1} is the total carbon store the year before t.

Presentation of Results

Simulation results are presented in several ways. The average total store and flux are presented on the spreadsheet inside the yellow colored box. These represent the value that would be found at the landscape level for a regulated system, that is one in which the disturbance is repeated at regular intervals. Trends in the total stores and flux are plotted against time in sheets entitled Stores and Flux, respectively. As a reference point, the mean stores for selected examples are also plotted on the stores graphs.

Example Simulations

Primary Succession. This spreadsheet simulates the simplest case in terms of carbon dynamics. In primary succession the ecosystem starts with little if any carbon. Therefore the initial detritus stores were set to 0. The result is that the carbon stores increase through time until an asymptote is reached (Figure 2). Moreover the flux is always equal to or greater than zero (Figure 3).

Figure 2. Change in carbon stores during primary succession.

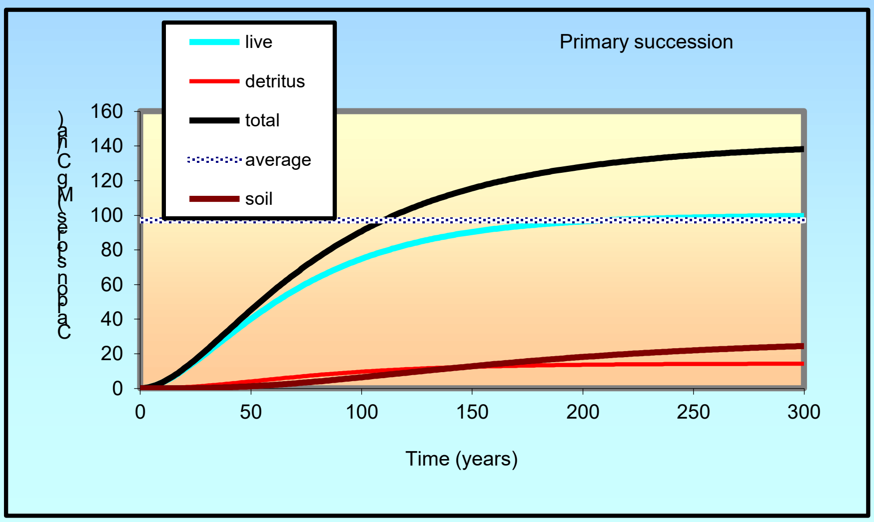
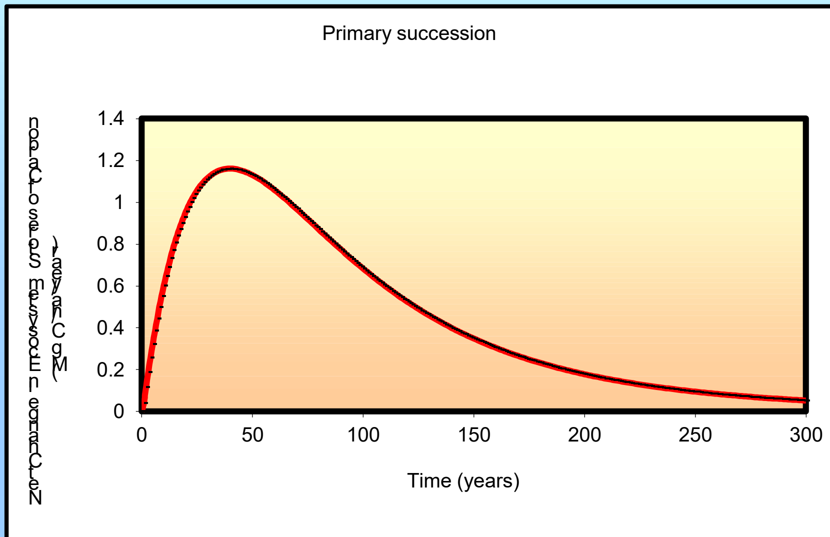
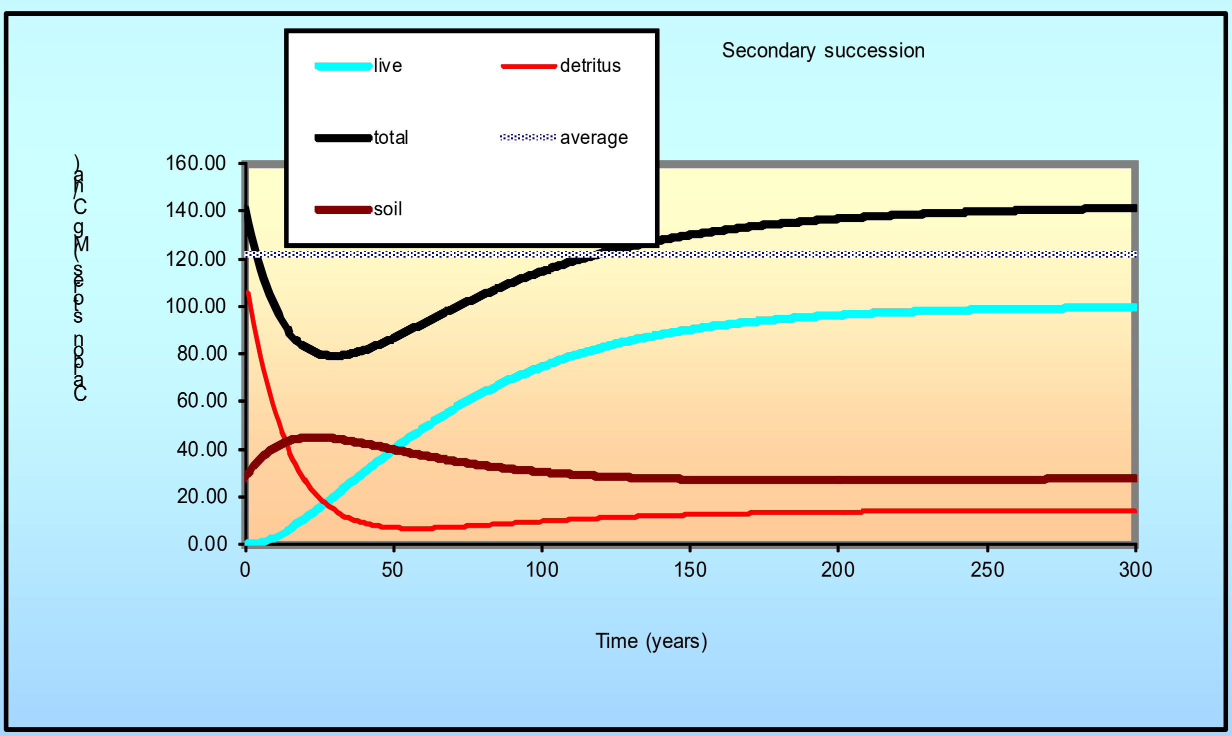


Figure 3. Change in the net flux of carbon into (positive) and out of (negative) a forest during primary succession.



Secondary Succession. This spreadsheet simulates a more complicated case in terms of carbon dynamics. In secondary succession the ecosystem starts with carbon usually in detritus and soils and sometimes in the case of moderate disturbances some stores in live pools. In this case the live carbon stores were reduced to 0 by the disturbance and the initial detritus stores were set to equal the sum of the live and detritus pools just prior to the disturbance. In secondary succession total carbon stores do not increase through time. Rather total carbon pools usually decrease for some time until increases in the live pool can offset the losses from the detritus and soils pools.



Soils stores decrease for a period then increase as the pulse of disturbance generated detritus forms well decomposed carbon (i.e., soil). Given enough time an asymptote in total stores is reached (Figure 4). These changes in carbon stores leads to a far more complex pattern of flux following disturbance. Right after the disturbance the flux is negative, indicating the ecosystem is losing carbon. After a period the flux crosses the 0 line and becomes positive. With enough time the flux converges on 0, however, in many real ecosystems disturbances come at shorter intervals than required to reach this asymptote (Figure 5).

Figure 4. Change in carbon stores during secondary succession after wind throw.

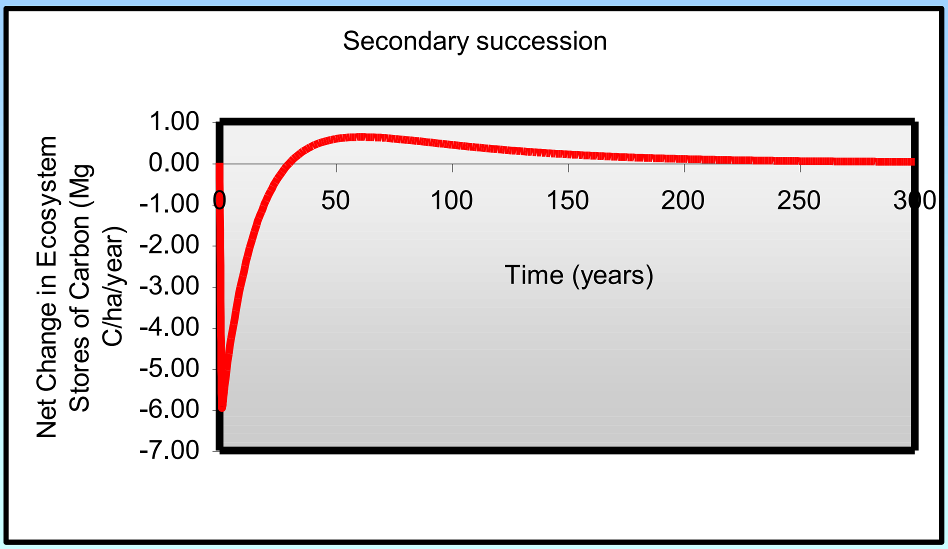
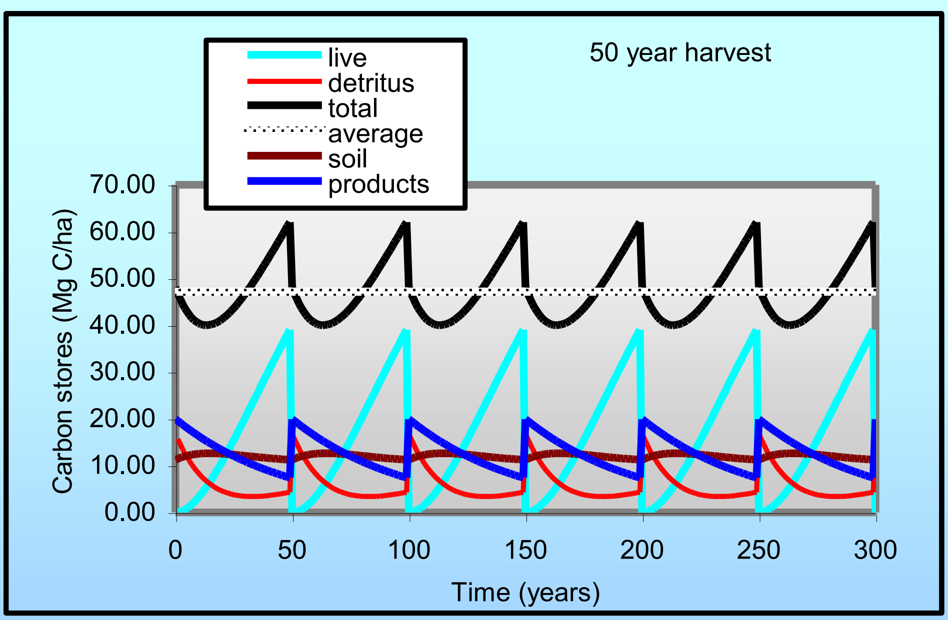


Figure 5. Change in net flux in carbon during secondary succession after disturbance by wind .



Managed Forest-50 year rotation. This spreadsheet simulates the influence of harvesting forests every 50 years. At each harvest 65% of the live stores is removed and 50% of that harvest is converted to long-term forest products that are lost to the atmosphere at a rate of 2% per year. The latter two parameters are set for values typical of temperate systems. Additionally, 50% of the detritus stores present before the harvest are lost via site preparation treatments such as broadcast burning. In this case the stores increase gradually and then rapidly decrease after each harvest (Figure 6). This is because the fire rapidly releases carbon as does the processing of forest products. The flux rates fluctuate around a value of zero, the rapid lost in carbon stores associated with disturbance caused a deep negative spike (Figure 7). This is followed by a gradual decrease in the negative flux that eventually becomes positive until the next timber harvest.

Figure 6. Change in carbon stores for a forest harvested on a 50 year rotation interval.

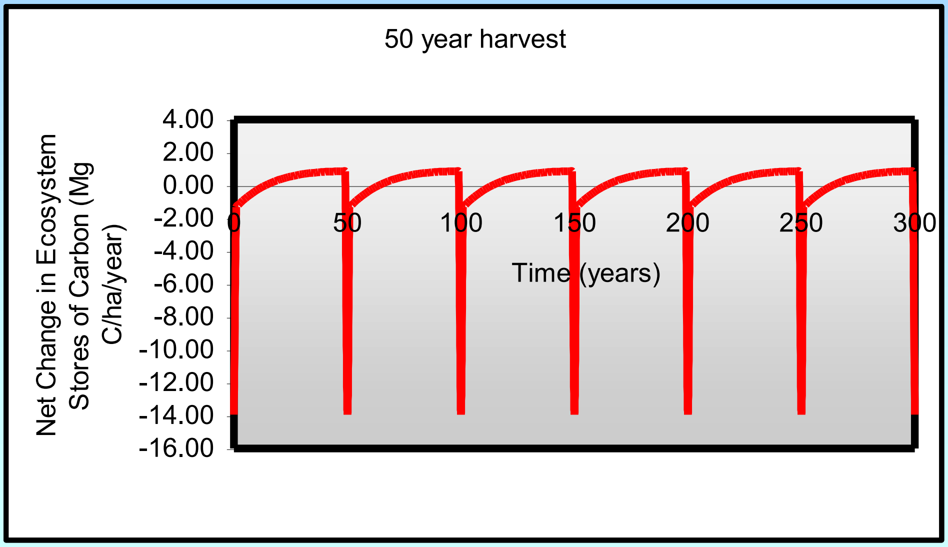


Figure 7. Change in net carbon flux over time for a forest harvested on a 50 year rotation interval.

Managed Forest-100 year rotation. This spreadsheet simulates the influence of harvesting forests every 100 years. The other settings are the same as those used in the 50 year rotation case. The general pattern of stores and fluxes are also similar with several differences. In the case of stores, the average store over the rotation is higher, reflecting part the longer time to accumulate carbon (Figure 8). In the case of fluxes the negative and positive pulses are more extreme than in the case of the 50 year harvest rotation (Figure 9). However, when the fluxes are averaged over the rotation length the value is very close to zero, the same as for the 50 year harvest rotation.

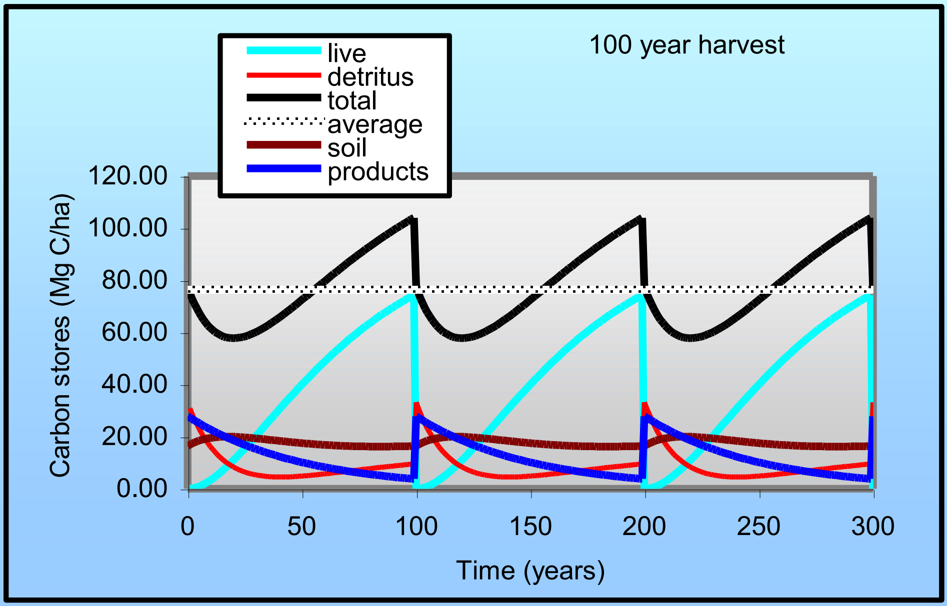


Figure 8. Change in carbon stores for a forest harvested on a 100 year rotation interval.

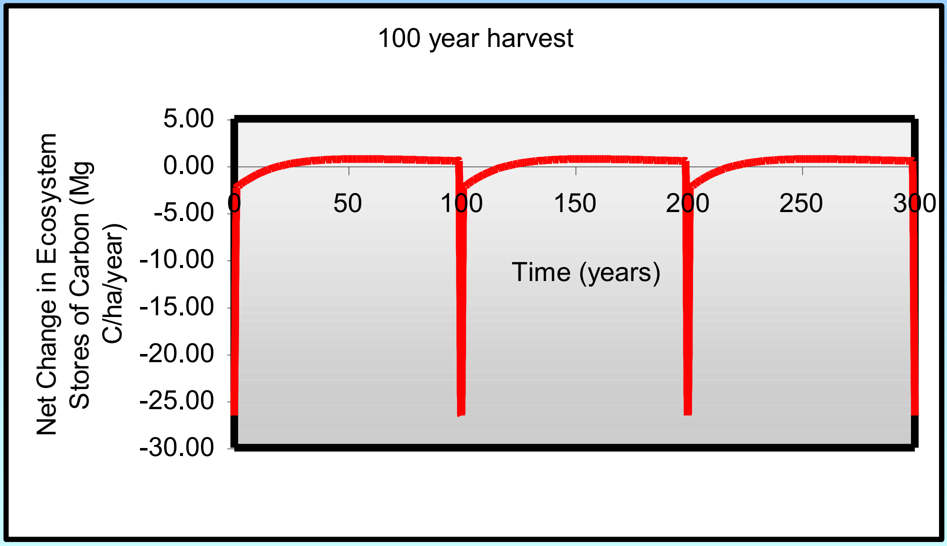


Figure 9. Change in net carbon flux over time for a forest harvested on a 100 year rotation interval.

Using the Models for Exploration

While the models have been parameterized to illustrate specific facets of the carbon sequestration problem, there is no reason one cannot alter these parameterizations. On each spreadsheet you will find a set of parameters that can be adjusted. You will notice that when a parameter is changed, the stores graphs do not oscillate about an average until the system has readjusted (Figure 10). That is the cycles have an underlying slope. One can eliminate this trend (make the cycles stationary) by adjusting the initial values of the detritus and forest products pools to match the last value of the simulation. You will also notice that the flux graphs are not balanced with respect to positive and negative periods if the parameters are changed from the original settings (Figure 11). This imbalance is also indicated by the fact the average flux over the simulation is not 0. By adjusting the initial stores as suggested above the average flux should converge on a value of 0.

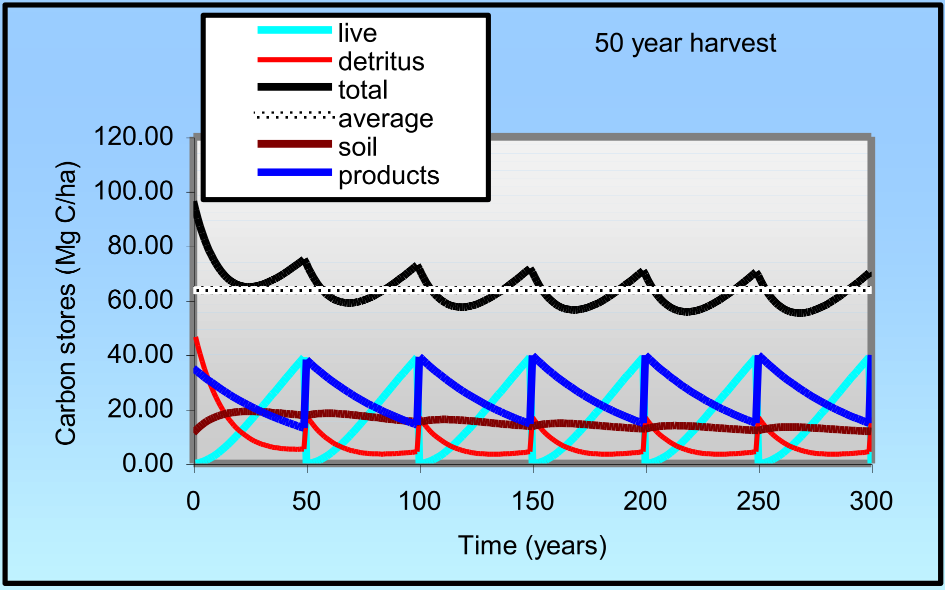


Figure 10. Decrease in stores as old-growth forest is converted to a 50-year rotation system.

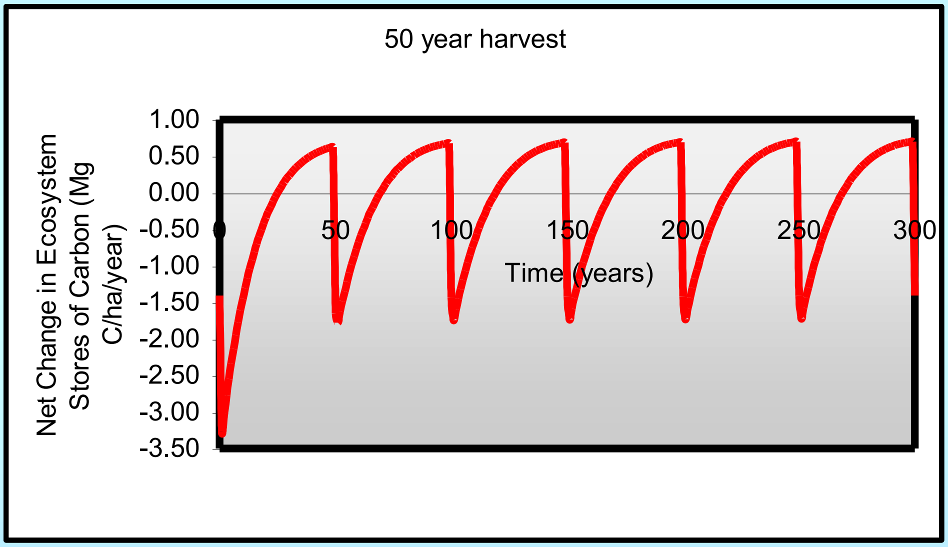


Figure 11. Change in flux after conversion of an old-growth forest to a 50-year rotation. Notice that only after several harvests does the positive portion of the cycle balances the negative portion of the cycle.

References

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