Integrating Systems with Different Time Horizons

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Introduction

In this report I explore how systems (i.e., ecosystems, feedstocks, and management systems) with different time horizons can be integrated. The basic problem I am examining is that systems with different time horizons, as defined by T, must be reconciled in the methodology proposed in the SAB report. Unfortunately the report is short on details on how this will be achieved and it does not examine the various methods for achieving this reconciliation. Moreover, while the report illustrates how individual systems might respond (e.g., Appendices C-E), it provides no example of how multiple systems might be reconciled and integrated. Nor does the report provide a scientific rational for the proposed integration method other than to suggest that an integrated model provides an integrated result. Although this is self-evident, it leaves unanswered the question of how the subparts of the overall integrated system will be treated other than to state that the T for the integrated system will be applied to all the subparts.

To provide some of the missing detail I first review how T is determined and the scientific basis of why systems have different time horizons. I then use these concepts to explore how systems with very different time horizons can be integrated by selecting an "overall" T. Rather than illustrate the single method proposed in the SAB report, I explore a variety of methods and discuss their strengths and weaknesses. I conclude by illustrating how the BAF's of the subsystems would be determined once the "overall" T is determined and contrast the two different methods of setting the "overall" T.

Determining the Time Horizon

In terms of the BAF, the time horizon of carbon response of a system, T, is defined as the time for a large majority of the difference in carbon stores between the reference and policy scenarios to be expressed. In theory T is reached when this difference ceases to grow and when the $NBE_{\Delta t}$ reaches zero. However, in practice T needs to be defined as the point at which either a very large share of the difference has been expressed (e.g., 99%) or alternatively when $NBE_{\Delta t}$ reaches a minimal level that is nearly zero. This is because the NBE_t response over time typically follows a negative exponential or natural growth function (see Appendix C and D). These functions have very long "tails" representing either trivial loss or trivial accumulation. For example, a system with an average carbon life-span of 10 years would have 50% of the response in 7 years, 95% of the response in 30 years, 99% of the response in 46 years, and 99.9% of the response in 70 years. Thus, substantially more time is required to add smaller and smaller amounts to the total response. Given this, the convention is to use either a proportion of the mass or absolute rate of change to determine the timing of the system. For the examples below I used two different methods to determine T: 99% of the final difference in carbon stores (mass-based) and the point at which $NBE_{\Delta t}$ fell to less than 1% of its maximum value (flux-based).

The Basic Science of System Response Time

We can think of systems that reach T earlier as being faster than those the reach T later. What determines the "speed" of a system in reaching T? Several factors determine when the difference in carbon stores between the reference and the policy scenario stabilizes, an indication T has been reached (SAB Report, Appendices B, C, D). The first major factor is the average time carbon stays in the part of the system responding. Specifically, the longer carbon stays in a system (i.e., ecosystem pool, feedstock, region, or globe) the slower the response time to a policy scenario. The length of time carbon stays in a system is described as the turnover time, which is defined as the average time carbon stays in the system. This relationship of turnover time and response time is why carbon can accumulate in soils and landfills for a very long time relative to annual plants (the former have much longer turnover times than the latter). Another major factor influencing system response time (i.e., T) is the rate at which a policy is implemented. Specifically, the slower a policy is implemented, the longer the system response time will be, and slower the response. To a large degree policy implementation is dependent on the harvest interval with annual cropping systems being implemented faster than long-term ones. However, implementation also depends on whether the policy involves a one-time change versus a series of changes over time, with the latter slowing system response more than the former. In addition, system response time is also determined by underlying changes in the environment, particularly if those changes interact more with the policy scenario than the reference scenario (see Cases 4 and 5 in SAB Report Appendix D).

Olson (1963) derived the mathematical relationship to predict when an ecosystem store reaches a steady-state. We can borrow from this derivation to predict when NBE_t reaches a constant level (which is analogous to a steady-state), because that is when T is reached. If the difference between the reference and policy scenarios follows a natural growth function we can define T as the time for X% of the difference to be expressed. Typically X% would be defined as 95% or 99% by convention to represent a large share of the change. The natural growth function to predict NBE_t is:

$$NBE_t = NBE_{maximum} (1-\exp(-k\, t))$$

We can rearrange this formula so that NBE_t is expressed as a proportion of the maximum at time t:

$$NBE_t / NBE_{maximum} = 1-\exp(-k\, t)$$

Since the timing of the natural growth function and a negative exponential equation are similar (they are complements) one can rearrange the terms to the latter as it is easier to solve:

$$1-NBE_t / NBE_{maximum} = \exp(-k\, t)$$

Taking the natural logarithm of both sides of the equation allows one to solve for k, the relative rate the difference increases per unit of time:

$$t=-\mathrm{Ln}\,(NBE_t / NBE_{maximum})/\, k$$

If 95% and 99% of being reached is used then, respectively:

$T_{0.95}$=-3/ *k* and

$T_{0.95}$=-4.6/ *k*

While these relationships are expressed in terms of k, one can also express them in terms of the turnover time which is 1/*k*.

Qualitative Examples of Response Times

We can test this general relationship between turnover time and time horizon of response by qualitatively examining several general cases. If the growing stock is the part of the system responding, then the response time is largely controlled by the interval of harvest, which is why annual crop systems respond more quickly than perennial ones and why long rotation systems respond more slowly than short rotation ones. However, system response is not only determined by the rotation interval of the growing stock. Other parts of the system can respond that are slower or faster than the growing stock and the overall system speed depends on the magnitude of this response relative to that of the growing stock. This is why overemphasis of the time dynamics of the growing stock fails to predict certain responses. For example, annual crop systems are thought to be fast response systems. However, an annual cropping system can have a slow response if the mineral soil carbon is the main pool responding to the policy change. The same mismatch between growing stock and system response times can occur for forests which are generally considered slow response systems. In the case of slash that is disposed by prescribed fire, the response time can be quite rapid relative harvest of the growing stock. That is because slash that is burned onsite has a very short turnover time relative to the trees in forests.

Possible Integration Methods

When system response times differ for the inevitable reasons described above, then there are several methods to reconcile and integrate them (although the SAB Report only describes one). One possible approach is to use the dynamics of the slower system as a “comparator” to standardize the other responses. This was the method proposed in the original report of 2016. Another approach would be to use the overall, integrated response of all the feedstock subsystems weighted by their abundance (as defined by their contribution to total emissions) to determine the “overall” T. This is the method proposed by the current SAB report. In addition, several other methods are possible including using a policy defined time horizon for all systems as well as using each subsystem’s T to evaluate the BAF of each subsystem. The merits and demerits of each are explored below in an example.

Exploratory Example of System Integration

In many regions a number of biogenic fuel stocks will be used, some with very rapid abilities to respond and other with very slow abilities. This raises the question of how feed stocks with very different temporal dynamics would be integrated. I explored this process using a set of theoretical systems with different values of T (Figure 1) that ranged from 2.5 to 320 years. For each of these systems the time that $NBE_{\Delta t}$ approached zero is indicated. To make the systems

comparable $NBE_{\Delta t}$ was rescaled to make the maximum value the same for all the systems. We see the same general response of $NBE_{\Delta t}$ with an early peak followed by a negative exponential decline. The main difference is that the slower the system, the more the time axis is stretched out.

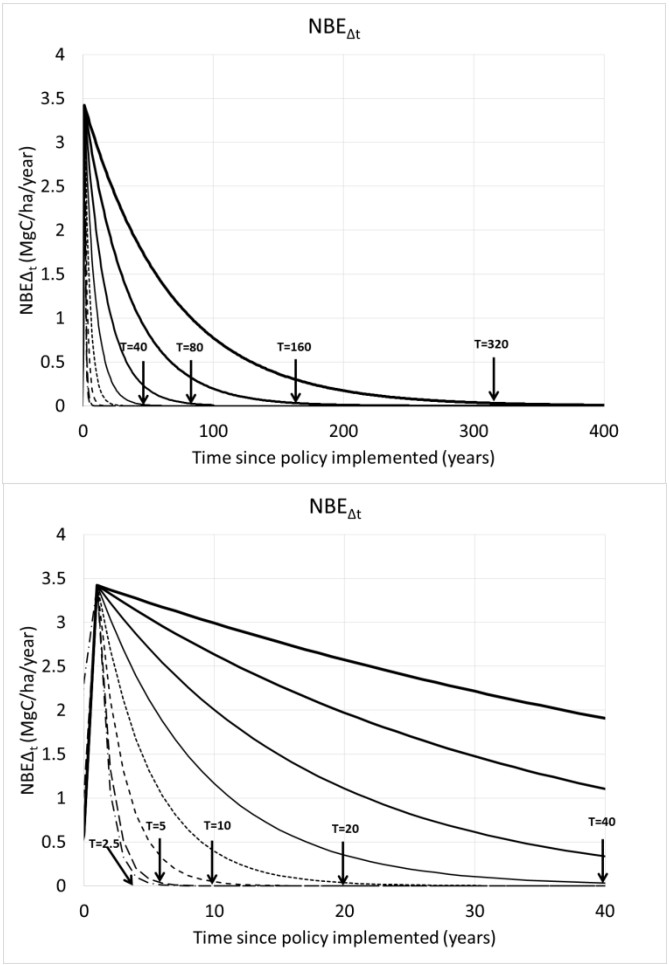

Figure 1. Illustration of how the rate at which NBE_t is changing as a function of time since policy implementation (lower panel shows detail of the"faster" systems).

In Figures 2 and 3 systems with different abilities to respond, as indicated by T, are compared for BAF_t and $BAF_{\Sigma t}$. The approximate point at which T is reached for each system is indicated by a numbered circle corresponding to the value of T. For both cumulative BAF's the value rises to a peak and then falls off with time. The faster the system is to respond, the lower the peak BAF is, the earlier it appears, and the faster it approaches zero as the time since the policy was implemented increases. This analysis indicates that while the peak BAF is reduced for rapidly responding ecosystems, it does not go to zero unless the ecosystem can instantly recycle the carbon released by biogenic fuel combustion.

To integrate these different dynamics a common timeframe needs to be selected. One method described above would be to select a time guided by a specific policy. However, this is problematical because it could distort the temporal signals given by the different systems. For example, if the system with a T of 80 years (see the vertical dashed line) was selected as the comparator (i.e., the system to which all other systems are compared), then those with a T of 160 and 320 years would have a BAF_t 1.8 and 2.7 times higher than the comparator system. In contrast, the system with a T of 40 years would have a BAF_t 0.52 times lower, that of the system with a T of 2.5 years would essentially be zero. Selecting a time of assessment that is very short can create problems if the BAF's for the slowest systems have not peaked. For example, if a T of 5 years is selected, then BAF_t of the slowest system (T =320 years) would be 4% lower than its peak value. Selecting the slowest system as the comparator would at least include all the other systems' carbon responses. Although the BAF's of the other systems would be lower than if a faster system was used as the comparator, this choice would not lead to all systems having a cumulative BAF of zero. That would be true for the fastest systems, but even those 2 to 4 times faster than the slowest system would have a BAF above zero.

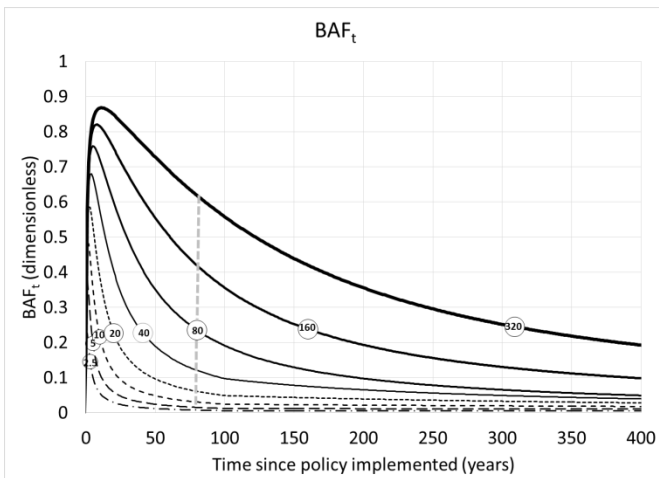

Figure F-2. Response of BAF_t for systems with different values of T.

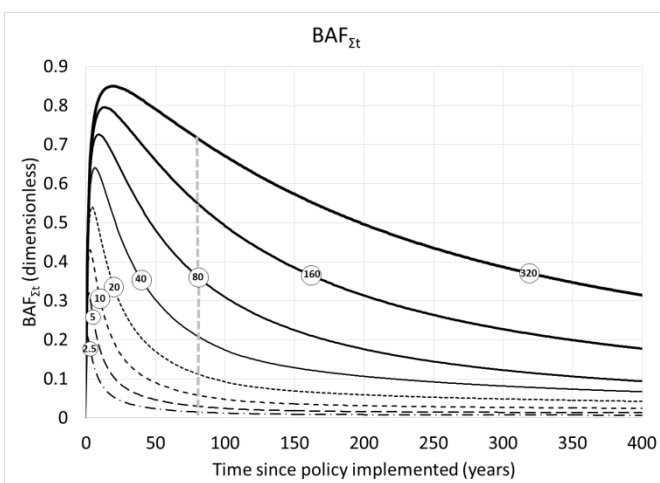

Figure F-3. Response of $BAF_{\Sigma t}$ for systems with different values of T.

Another possibility to reconcile systems would be to use the cumulative BAF at each system's T. Plotting the value of BAF at time T for all the systems reveals the problem with this approach (Figure 4): the values of cumulative BAFs and the peak value of $BAF_{\Delta t}$ are similar over a very large range of T (i.e, 20-320 years). This method would effectively ignore the different temporal dynamics of systems; however, it would distinguish very fast systems (T<10 years) from the rest.

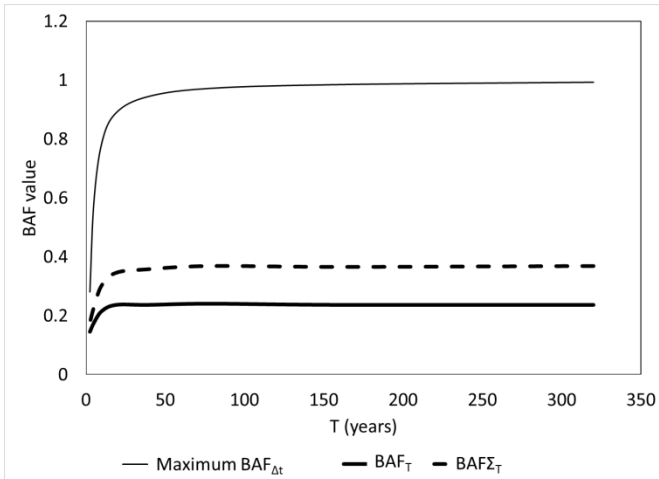

Figure F-4. BAF of different systems as a function of T, the time horizon.

Each of the systems of reconciliation described above is somewhat artificial, although as noted using the system with the slowest response time does at least assure that all the carbon effects are completed. However, even that system is limited because it does not address the abundance of subsystems. This causes a problem because the slowest system might be quite rare, but it would determine the T for all the other systems. Therefore functionally it would make more sense to not only include the timing, but also the relative emission contributions of the different systems. As described in the SAB report, the basic method would be to analyze the integrated system and to use the dynamics of the overall system to define an overall T.

An example of this integrated approach is illustrated in Figure 5. In this example two systems with very different dynamics were combined in different combinations ranging from 100% of the fastest (T=5 years) to 100% of the slowest system (T=160 years). The various combinations ranged between these two endpoint systems. The presence of the slow system leads to a long "tail" in the overall system, which lends some support to selecting the slowest system as the comparator. However, when T is selected based on either the amount of the maximum NBE_t achieved (in this case 99%) or a very small fraction of the peak $NBE_{\Delta t}$ (in this case 1%), the overall T of the combined system is a function of the mixture of the subsystems (Figure 6). As a reference, I also examined a very simple method in which the two end member values of T were averaged weighted by abundance (i.e, a simple mixture model). This indicates that while the integrated method responds to the mixture, it is more conservative than the simple mixture model of T's. The integrated method based on a minimum fraction of $NBE_{\Delta}t$ is more responsive than

that based on the fraction of maximum NBE_t achieved. It should be noted that the fraction of maximum NBE_t achieved when $NBE_{\Delta}t$ is 1% of the maximum value is not necessarily 99%. Specifically, in this example the percent of the maximum NBE_t achieved was above 97% for mixtures in which there was at least 25% of the slow system. When the fraction of the slow system dropped to 5% slow, the flux-based T was reached when 90% of the total NBE_t was reached. While I do not have a recommendation as to which criteria to use to select T, it would influence the value of the overall T and the amount of carbon effect considered.

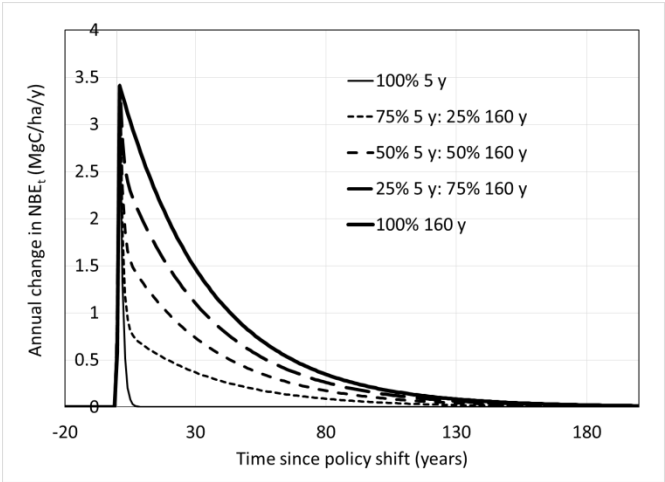

Figure 5. Annual change in NBE_t (i.e., $NBE_{\Delta t}$) as function of time since policy shift and system mixtures.

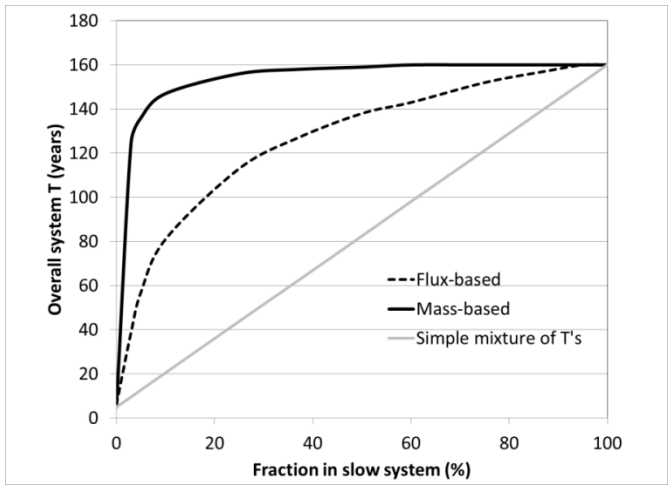

Figure 6. Overall T for integrated systems as a function of system mixture.

The final step in estimating the cumulative BAF of each of the component systems would be to evaluate the cumulative BAF of each of the systems using the overall T. This is illustrated in Figure 7 for a system in which the overall T is selected based on 1% of the maximum $NBE_{\Delta t}$ value. Both cumulative BAF's are most responsive when the slow system falls below 25% of the overall mixture. Moreover the slower systems are more responsive than the faster ones when the slow system is more than 25% of the mixture. This integrated system can be compared to that in which the slowest system is the comparator by using the value when the slow system is 100% of the mixture, which is essentially the recommendation in the last SAB report (i.e., 2016). For systems with T's less than 20 years, the cumulative BAF is not that different using the either the integrated method or the slowest system as comparator method. For systems with T's greater than 80 years, the two systems differ substantially. Although the method using a fraction of the mass difference is not illustrated, it is more conservative than the flux-based method and would likely be less responsive than the flux-based method. This would mean that the integrated and slowest system as a comparator method would be more similar than indicated in Figure 7. EPA would need to make a policy decision of which method of selecting the overall T given that each method provides different estimates of cumulative BAF.

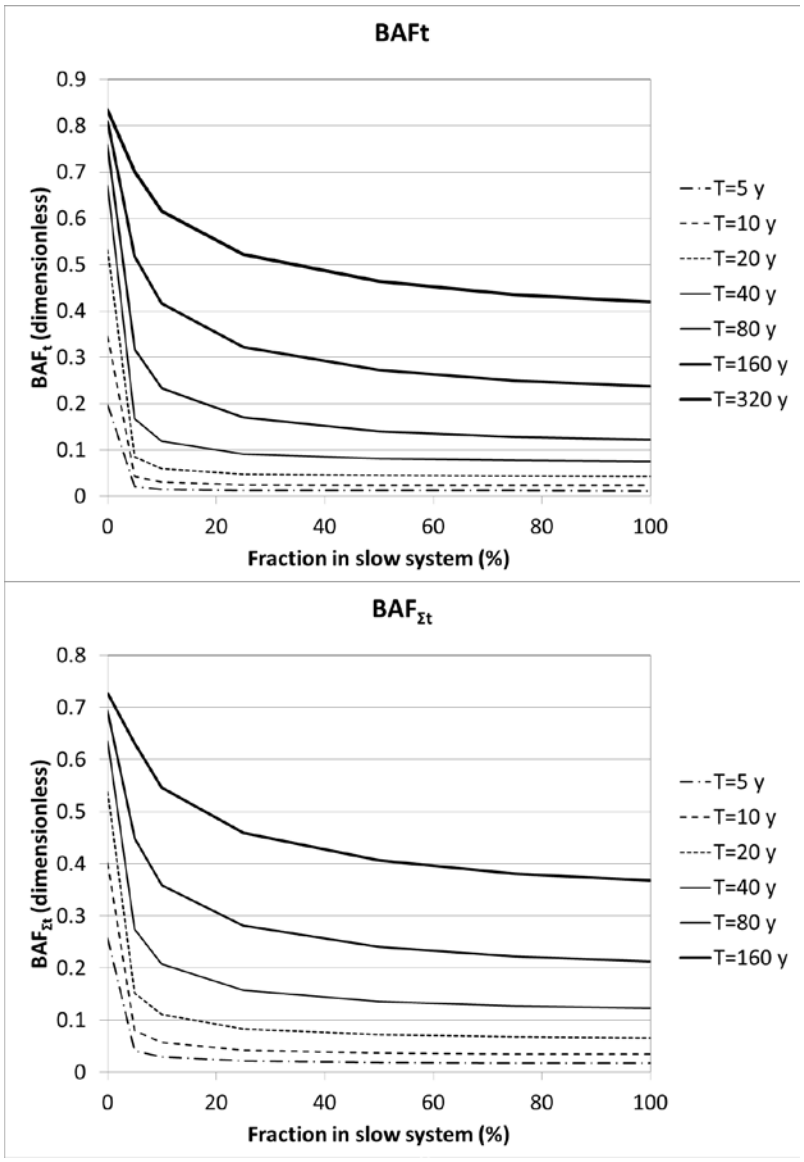

Figure F-7. Example of using the overall T based on a minimum flux to determine the cumulative BAF for systems with different values of T.

References

Olson, J.S., 1963. Energy storage and the balance of producers and decomposers in ecological systems. *Ecology*, *44*(2), pp.322-331.