Mark E. Harmon

Carbon Sequestration in Forests

Addressing the Scale Question

Mark E. Harmon

ABSTRACT

Forests may have an important role to play in removing carbon dioxide from the atmosphere. However, the extent of their role depends not only on the area available but also the management system that is applied and whether it is based on sound scientific principles, including those of basic ecosystem science. One aspect of ecosystem science that generally has been overlooked in forestry-related carbon projects is that of scale. By paying closer attention to scale, seemingly contradictory statements concerning forest management and carbon sequestration can be resolved, which can lead to the development of a viable carbon sequestration policy.

Keywords: carbon sequestration; ecosystem management; policy; scale

Forests have the potential to store a great deal more carbon than they do. Exploiting this potential is one of several proposed strategies to temporarily slow the increase of atmospheric carbon dioxide concentrations. However, before such a policy is generally accepted several major issues involving forests need to be reconciled.

Not all forestry-related projects are equally likely to sequester carbon; some may actually release carbon to the atmosphere. The carbon sequestration implications of afforestation and reforestation projects are relatively simple and have received a great deal of attention (Sedjo et al. 1997). In contrast, the role of more traditional forestry practices for increasing carbon sequestration are less clear, with a great deal of confusion about which practices run counter to the goal of increased carbon sequestration. On one hand, many forestry professionals believe that young forests are optimum

Above: **Old-growth forests, such as Valley of the Giants in the Oregon Coast Range, store some of the greatest amounts of carbon.**

for sequestering carbon because they are growing faster than older forests. Moreover, older forests have more dead trees and decomposition, and hence they should release more carbon than younger forests. Together these two observations suggest that replacement of older forests should enhance carbon sequestration. On the other hand, many published, peer-reviewed studies on this subject have concluded that the replacement of older forests by younger ones will result in a net release of carbon into the atmosphere (Cooper 1983; Harmon et al. 1990; Dewar 1991; Schulze et al. 2000). Before a sensible policy on forest practices and carbon sequestration can be developed, we must understand the basis of these two contrasting views.

The interesting thing about this debate, aside from its heated nature, is the fact that there are elements of truth in both views. This is probably why each side views their argument as convincing. The resolution of these contrasting views lies in understanding the scale (which, unfortunately, often is not stated) the statements address. By specifying the scale issue specifically, one can understand not only which statements are true versus false, but also the scale most relevant to setting forest carbon sequestration policy.

This article reviews the issue of scale and carbon sequestration in forests. It draws primarily from ecosystem science, which is logical given that carbon sequestration is primarily an ecosystem process. The article reviews the concept of scale, illustrates its use in resolving seemingly divergent views, and concludes by suggesting the scale that is most appropriate to the question of how forest management can be used to increase the sequestration of carbon from the atmosphere.

What Is Scale?

Although one can view the world from the smallest increment of time or space or from the most elemental of processes, it is often helpful to view the world through larger "windows." These windows that define (often arbitrarily) the spatial, temporal, and process resolution, are the scales used by an observer. Although some argue that scales are not natural phenomena, there is no debate about their utility. For example, forest growth is often best measured from year to year or in some cases decade to decade rather than from one instant to the next, despite the fact that trees actually grow from one instant to the next. The same is true for spatial extent. In theory we could measure the amount of carbon stored in an infinitesimally small volume of soil, but we usually measure it in a profile of 1 cubic meter or so, and often average it over even larger extents. We may also choose to examine processes at a level above the most fundamental ones, in part because there are so many intermediate processes that the propagation of errors becomes potentially excessive.

Even though using scales has a clear benefit, it also has a cost in the sense that a measurement may only be relevant at the scale at which it was taken. That is, certain measurements and observations may directly apply to broader or coarser levels, while others may not. To avoid this pitfall the process of defining a problem should always include specifying a spatial, temporal, and process level. A lesson from ecosystem science over the past 25 years is that when this is not done (or when the dimensions of scale are tacitly assumed), one can develop seemingly irresolvable conflicts (Allen and Starr 1982; O'Neill et al. 1986). This lesson will now be applied to the question of forest practices and carbon sequestration.

What Is the Sequestration System?

An issue related to process resolution involves the definition of the forest carbon sequestration system. This includes not only the parts, but also the processes involved. Given that trees and forest products are the focus of forestry, it is only natural for the practicing forester to assume that these are the only relevant pools to consider. In fact, for many reforestation projects these are the only pools considered. However, they are only part of the forest carbon sequestration system, and for a full accounting one must also include detritus and soil. The processes that need to be considered include not only tree growth, but also photosynthesis and plant respira-

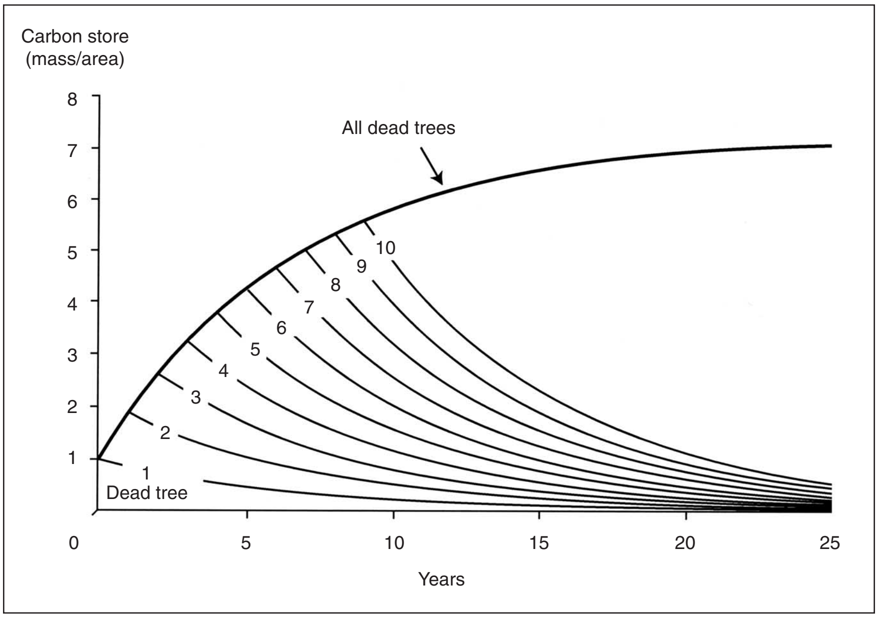

Figure 1. **The loss of carbon from an individual tree versus the accumulation of carbon in a collection of trees. In this example, dead trees are being added to the ecosystem. Each dead tree loses carbon as it decomposes; however, as a collection (shown by the upper line) the dead trees can increase carbon stores over time.**

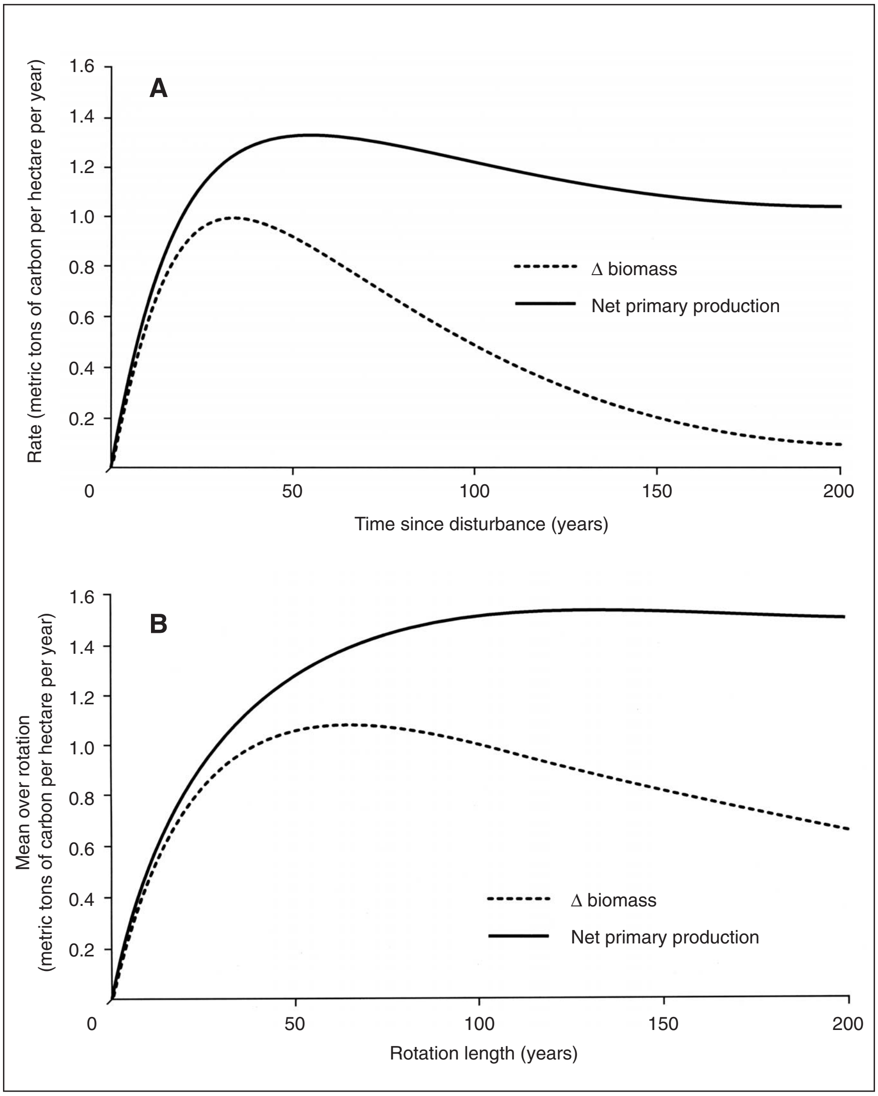

Figure 2. **The theoretical trend in net primary production (NPP, or gross growth) and change in live biomass stores (Δ biomass, or net growth) for a forest system that has been disturbed by clearcut timber harvest.**

tion, tree death and litter production, decomposition and the formation of stable organic matter in the forest floor and soil (including charcoal), disturbances such as timber harvest and fire, as well as the manufacture, use, and disposal of forest products. Substitution of fossil fuels may also be considered in a forest sector analysis; however, this is often done at a level of resolution larger than the forest sector per se, one that includes all carbon processes such as fossil fuel use, cement production, and others.

An important criterion to use in defining the forest carbon system is to create a "closed" system, or one in which all carbon is accounted for and conserved. This is important because the flux to the atmosphere is usually not directly measured. Rather it is solved by the difference of all the other terms. Therefore, by excluding some pools it is possible to create a misleading impression of the impact of some forest practices. For example, confining the system to just trees inevitably leads to the conclusion that young forests sequester carbon faster than older forests. However, young forests are often associated with large amounts of slash from the previous harvest, and when the decomposition of this material is considered, it may turn out that the complete system is actually losing carbon to the atmosphere even though the younger trees are growing at a rapid rate. In some cases, such as afforestation projects, only trees and forest products are considered, but it turns out this is a special case in which excluding the other pools will systematically underestimate carbon sequestration rates. In far more situations overestimation of sequestration occurs when certain pools are excluded, which has led to the notion of the minimum number of pools that need to be considered for different types of projects.

How Is Carbon Sequestered?

The traditional explanation of carbon dynamics in forests starts with photosynthesis and considers losses via respiration of the plants and the decomposers. There is nothing inherently wrong with this explanation, but it leaves the distinct impression that anything associated with decomposition leads to a loss of carbon from the forest. This explanation also is used to support the conclusion that developing younger, healthier forests should remove carbon faster than older, decadent forests with high rates of mortality and decomposition. However, because of scaling considerations this not necessarily true at the scale of an ecosystem.

At the scale of individual pools, the tendency is to focus on living plants as the only long-term store of carbon. As stated above, the rationale is that because respiration represents a carbon loss, any pool that only has respiration without accompanying photosynthesis cannot accumulate carbon. Although this is true at the scale of an individual dead leaf or tree, pools such as detritus, soil, and forest products can also store carbon over the long term.

The latter three pools cannot take carbon directly out of the atmosphere via photosynthesis; they can, however, accumulate and permanently store carbon if the inputs to these pools are maintained through time (Olson 1963). It is true, for example, that once a tree dies it begins to decompose and thus lose carbon. It is equally true, however, that if trees die at a steady rate, then as a collection the mass of carbon stored in the dead tree pool can grow and thus store carbon *(fig. 1)*. Conversely, when analyzed at the individual level it is clear that living plants are not permanent stores—individuals and parts of those individuals are always dying. They are replaced by other individuals and parts that allow this live pool to permanently store carbon. The confusion concerning which pools can permanently store carbon is therefore largely a confusion over scale, that is, between transience at the level of individuals and permanence at the level of a collection of individuals.

Influence of Temporal Scale

In comparing the rates of carbon uptake of forests, one has to be careful about the time period being considered (i.e., the temporal scale). Let us take the statement that young forests remove carbon from the atmosphere faster than older forests. Consider the net rate that living plants remove carbon from the atmosphere—the rate of net primary production, or NPP (this is equivalent to gross growth in forestry terms). If one is considering the periodic NPP (i.e., the average value over a specific interval), then it is true that some young forests are more productive than older forests. However, there are also periods when young forests are less productive than older forests.

In the example shown in *figure 2,* the periodic NPP increases immediately after disturbance, reaches a peak, and then declines. The reason for the increase is well known: Trees take time to create the foliage, roots, and branches required to capture the light, water, and nutrients required for maximum photosynthesis. Because no disturbed forest starts with this level of production infrastructure, it follows logically that no young forest can start at the maximum. The reason for the decline with age is less well known and is an active area of ecological research (Ryan et al. 1997). The decline is due in part to increases in the respiration required to maintain the trees, but other factors including hydrologic limitations and nutrient availability may be involved. Regardless of the cause, NPP does not decline to zero in old forests. Therefore, there are many old forests just as productive as some young forests. Perhaps they are not as productive in terms of net biomass or volume accumulation, but this is a matter of where the carbon is allocated, not of ecosystem production per se.

If one considers the average production over the length of a rotation, then older forests may be just as productive as younger ones. This is because no forest can be X years old without having been X–1 years old. Foresters have acknowledged this scaling effect when they use terms such as mean annual increment. The same temporal adjustment can be used to look at the mean NPP or carbon sequestration over the rotation. This indicates young forests can be less productive than older forests both in terms of NPP and the net accumulation of carbon in live biomass *(fig. 2b).*

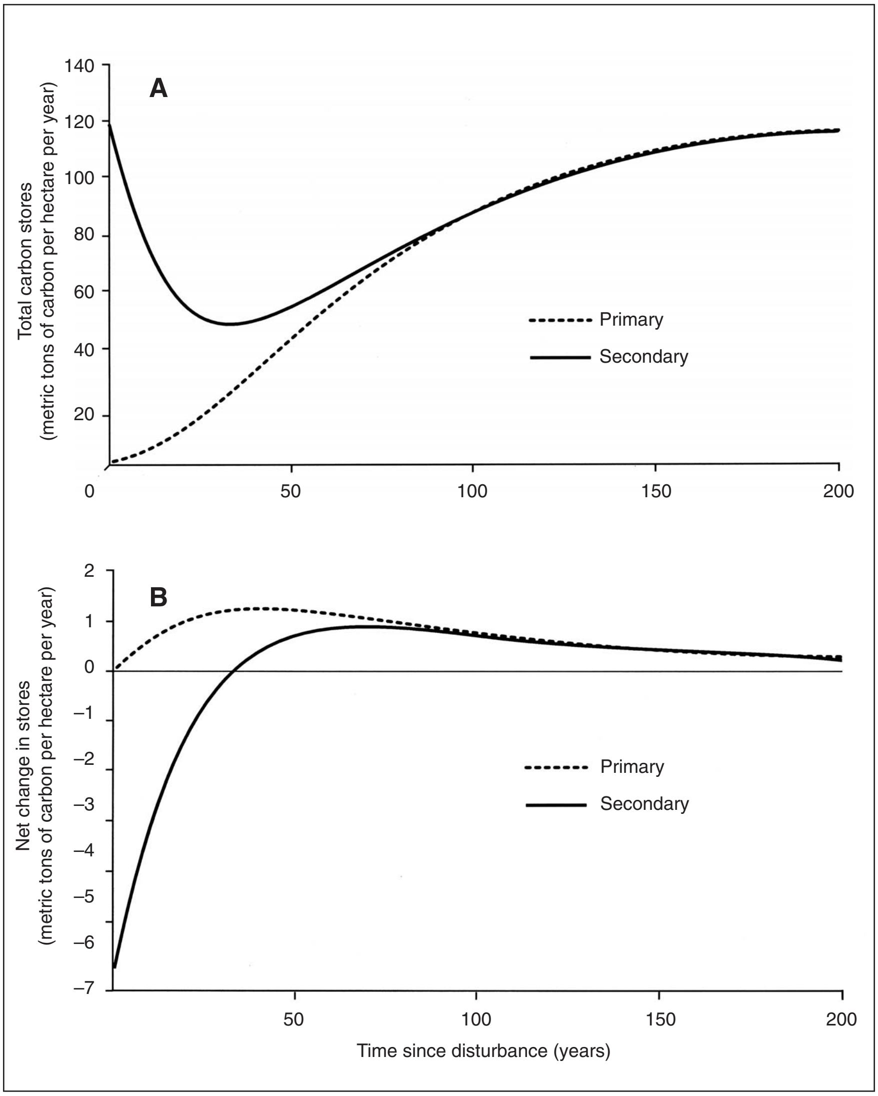

Figure 3. **Temporal changes in total carbon stores for primary versus secondary succession (in this case, a windthrow). For illustration purposes the time dynamics of all live and dead components is assumed to be equal for the two, although in primary succession the increase in stores is usually slower than in secondary succession.**

Uptake–Release Variations

From much of the popular discussion of carbon sequestration one gets the impression that forests can remove carbon from the atmosphere in perpetuity. Actually, this is not the case. To understand the reason, one needs to examine the pattern of carbon accumulation during succession. Recall that there are two basic types of succession: primary and secondary. In primary succession the initial organic carbon stores of all forms are essentially zero. As plants grow they add carbon not only in their live parts, but also as litter, detritus, and soil *(fig. 3).* Given enough time, the ability of the ecosystem to accumulate additional carbon

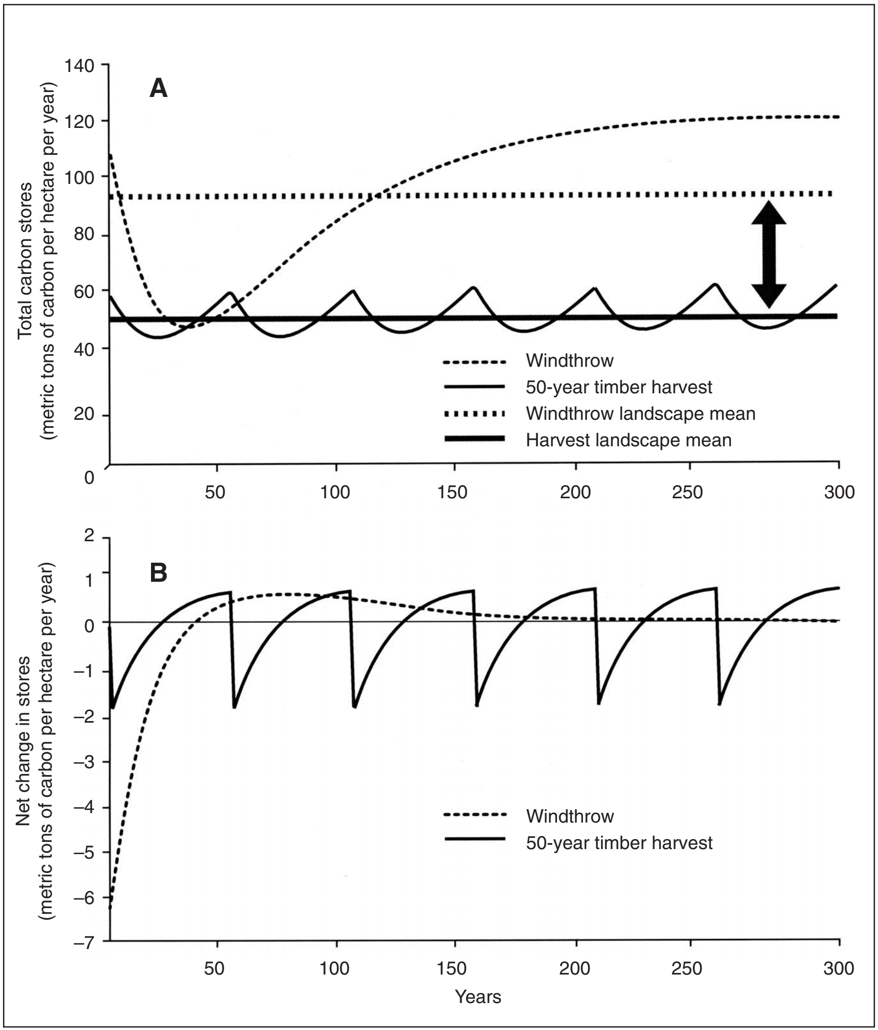

Figure 4. **Temporal changes in mass and net carbon sequestration rates for two different disturbance regimes: complete windthrow with a return interval of 300 years and timber harvest with a mean rotation of 50 years. For the timber harvest regime it was assumed that 65 percent of the live biomass was harvested (i.e., the entire bole) and that harvest was all converted to forest products with an average lifespan of 50 years. The horizontal lines in A indicate the mean landscape store of carbon for the two disturbance regimes. When averaged over the 300-year period, the net change in carbon stores for both disturbance regimes is zero, indicating both systems are balanced with regard to carbon sequestration at the landscape scale. The difference in the two disturbance regimes at the landscape scale is therefore one of stores, not net change. The arrow on A indicates the potential net change in stores caused by moving from one disturbance regime to another.**

theoretically approaches zero because the rate that new material can be added is equal to the rate it is lost through mortality and ultimately decomposition or consumption by fire. This relatively straightforward temporal pattern has been documented in much of the classic literature on succession (Olson 1958).

The temporal pattern for secondary succession is far more complex, in part because the disturbance that initiates the succession also leaves carbon behind in the form of detritus and soil carbon (Bormann and Likens 1979). This legacy of carbon begins to decompose, and in most cases this loss exceeds that of the growth of the establishing vegetation *(fig. 3).* Of course, in some cases growth can exceed decomposition losses even early during secondary succession, most notably old-field succession. This is because of the extensive loss of soil and detritus carbon associated with the cultivation of some crops. However, succession after forest disturbance usually leaves enough residual material that a period of loss starts the succession. As the legacy carbon decreases and the ability of the vegetation to photosynthesize increases, the ecosystem comes to a temporary balance. This is followed by a period of net uptake as growth of the live pools exceeds decomposition losses. With enough time, however, the amount of production of the live parts is offset by losses via decomposition. This final balance is never exactly achieved. For one thing, periodic variations in fine-scale disturbances (e.g., individual tree death) and climate variables cause this balance to shift slightly from time to time. Furthermore, long-term trends in these controlling factors may cause the ecosystem to seek a new balance. However, the idea that if variation in these "driving" variables ceased the ecosystem would come to a balance is still theoretically valid.

Let us now revisit the statement that young forests remove more carbon from the atmosphere than older forests. For primary succession and secondary successions with little carbon legacy, that statement is true for the periodic net carbon accumulation of the forest ecosystem as long as the forest is not too young to have developed its production infrastructure. The statement is definitely not true for secondary successions that leave a substantial carbon legacy. In fact, because of this legacy, many young forests lose far more carbon than old-growth forests when viewed on a periodic basis. Although old forests have a substantial amount of dead and dying material, these losses are roughly offset by the production of this material. Ironically, it is the very production of all that dead and dying material that prevents the older forest ecosystem from being a net carbon source to the atmosphere.

Storage with Disturbances

Given the temporal patterns presented in *figure 4,* we can imagine viewing the forest carbon system at the scale of one location or stand over a long time period. Over time we would see that carbon is removed from or added to the atmosphere depending on the time since the last disturbance. It would therefore appear at the stand scale that when forests are disturbed (and they all eventually are) carbon is not stored permanently. However, viewing at a larger spatial extent, one in which many age classes are present, would reveal that although some stands are releasing carbon, others are removing it and still others may be in a balance.

To assess the net carbon sequestration implications at the landscape scale, one needs to average the net carbon sequestration of all the stands in that landscape. It follows that if all forests in a landscape are eventually disturbed, then all landscapes must have areas that are increasing in carbon stores while others are decreasing. Furthermore, if the disturbance process is constant through time, creating a constant age structure, then each landscape is in balance not only in terms of age structure but also in terms of carbon stores, despite the fact that individual stands are being disturbed. This new landscape-level behavior of the system is analogous to the previous argument about carbon sequestration in an individual tree versus a collection of trees.

Now let us again revisit the statement that young forest systems remove more carbon than older forest systems. This statement is actually false at the landscape scale if we are talking about relatively constant disturbance regimes *(fig. 4)* because, given a large enough area and enough time, both systems will be in balance with the atmosphere.

There are three possible reasons that carbon sequestration at the landscape scale is not in balance. First, no disturbance regime is perfectly constant in terms of frequency and severity. For example, in some years more area is disturbed than in other years, which causes the landscape to release carbon to the atmosphere in some years and remove it in others. Second, and more importantly, when there is a shift from one disturbance regime to another, the landscape-level stores adjust to a different balance. If the disturbance regime becomes less severe or less frequent, then the landscape will store more carbon and hence remove carbon from the atmosphere. If the disturbance becomes more severe or the mean interval between disturbances decreases, then the landscape will store less carbon and hence add carbon to the atmosphere. This is the reason that the conversion of older forests to younger forests releases carbon to the atmosphere—increasing the frequency of disturbance to create a young forest system leads to a loss of carbon at the landscape scale. Third, landscapes may release or remove carbon if the underlying factors controlling NPP, growth, mortality, and decomposition change. For example, increasing atmospheric carbon dioxide may increase NPP, which will in turn increase the store of live trees, detritus, soils, and forest products derived from that landscape.

Although the balance between the second and third set of processes currently is a matter of scientific debate, it is probably safe to conclude that the changes in land-use-related disturbance have dominated until recently and that future landscape dynamics will be dominated by a combination of the two. It is also probably safe to conclude that the projected increases in NPP associated with increases in carbon dioxide concentrations and increased temperatures are far too small to completely offset the losses associated with conversion of older forests to younger forests.

Searching for the "Correct" Scale

One conclusion from the preceding discussion is that there is no single correct scale to assess the effect of forestry practices on carbon sequestration. To judge the effectiveness of a practice it is best to examine it over a range of scales. The mechanisms explaining a behavior often lie at a finer level of resolution, whereas the consequences of a behavior are generally found at a broader level of resolution. Another general conclusion is that just because a behavior occurs at a finer scale (i.e., shorter time, smaller space, more fundamental process) does not mean this behavior translates directly into a broader level of scale. This is because other processes may alter or limit that behavior. Despite these caveats the long-term, landscape scale is a particularly useful one to examine forest carbon policy. Policies are likely to be carried out at this scale, and it is at this level that many seemingly contradictory behaviors are resolved. Although assessments of "leakage" effects will require one to move beyond the landscape level to see if changes in one landscape have unintended negative consequences on another, an assessment at the landscape level will usually reveal whether a policy has the potential to increase or decrease the carbon stores of forests.

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Mark E. Harmon (mark.harmon@orst.edu) is Richardson Professor in Forest Science, Department of Forest Science, Oregon State University, Corvallis, OR 97331-5752.