Carbon and Biomass Dynamics in Missouri Forests and Implications for Climate Change

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Executive Summary

Atmospheric carbon dioxide (CO_2) gas has increased over the past century due to human activities that burn fossil fuels such as coal, petroleum, or natural gas. With greater concentration of CO_2, the atmosphere retains more heat and results in greater potential for change in global and local climates. Forests play a critical role in removing CO_2 from the atmosphere and storing it in plant material or belowground in the soil.

Trees and other photosynthetic plants are unique in the carbon cycle because they take up CO_2 from the atmosphere. Through photosynthesis, which is powered by sunlight, trees convert atmospheric CO_2 into carbon-based molecules that become wood and other tissues. The quantity of wood in a tree or in a stand of trees is measured as biomass, which is the weight of a tree and its component parts. Approximately half the dry weight of a tree's biomass is carbon (C). The more biomass that a tree or a stand of trees contains, the greater the quantity of carbon stored in that tree or stand. As trees and stands grow and accumulate biomass and carbon, they reduce the amount of CO_2 in the atmosphere.

Because approximately half of the carbon stored in forests is within aboveground biomass, the dynamics of carbon accumulation and storage within forests parallel those of wood production. Old forests store high amounts of carbon, typically reaching a saturation point in an old-growth stage. However, young forests that are growing vigorously have the greatest rate of carbon accumulation, rapidly pulling carbon from the atmosphere to convert to biomass. It is impossible to maximize both carbon storage and the rate of carbon accumulation in forests, and there are biological limits to the capacity of forests to store carbon and offset atmospheric CO_2 emissions.

Wood products play an important role in long-term carbon storage. For example, the quantity of carbon stored in the wood used to construct a new house offsets as much as 100 metric tons of atmospheric CO_2 and secures it for roughly the next 100 years. The benefits of using wood products are amplified if those wood products are used as substitutes for materials that require intensive energy for production such as steel, cement, glass, plastic, and insulation. In addition to the direct benefit of having carbon stored in the wood products, the fossil fuels that would have otherwise been required to manufacture the alternative products are no longer necessary.

Natural Climate Solutions are relatively low-cost management practices that are compatible with natural forest ecosystem dynamics and reduce atmospheric CO_2. They include activities that establish or replace forests (i.e., afforestation or reforestation); reduce risk of carbon loss from forest health threats or disturbances; manage existing forests to increase storage or accumulation of carbon; and reduce greenhouse gas emissions. Silvicultural practices that increase growth and the output of wood products are well-established examples.

Forest management decisions take into account a wide range of ecosystem services such as maintenance of biodiversity and forest protection. These are often compatible with carbon management because they maintain healthy, productive forests, even if carbon storage may not be maximized as the explicit objective. In Missouri and elsewhere there are published forest management guidelines that help ensure the long-term sustainability of forest ecosystems. Increasingly, forest management and silvicultural considerations include assessments of how future climate change will affect long-term forest change.

Examples of forest management practices that have positive effects on carbon, through either carbon storage, accumulation from the atmosphere, or offsetting other types of emissions, include:

1. Keep forests as forests. Forests accumulate and sequester carbon as they grow.
2. Use afforestation (tree planting) to increase the total area of forests. Forest ecosystems sequester more carbon per acre than other land cover types.
3. Make informed choices when selecting a stand's future species composition; over time climate change may alter species suitability for a given site.
4. Quickly regenerate forests that are disturbed by harvest, insects, disease, wildfire, or severe weather.
5. Protect forest soils.
6. Maintain urban and suburban trees and forest communities.
7. Keep forests healthy; trees that die cease to store carbon.
8. Keep forest stands fully stocked so the available growing space is fully utilized.
9. Manage to create "resilient carbon". Resilience allows stands and landscapes to recover from unwanted forest disturbances.
10. Produce wood products. When harvested trees are turned into wood products, the carbon in those products stays stored there for the product's useful life.
11. Substitute wood products for alternative materials that require high energy to produce.
12. Manage proactively to anticipate future climate change. It is not a matter of whether the climate will continue to change, but how much it will change.
13. Follow best management practices for forests, soils, and watersheds.

Forest management practices that increase the quantity of carbon stored in trees are widely viewed as beneficial. However, the annual quantity of CO_2 emissions resulting from burning fossil fuels greatly exceeds the capacity of forests to sequester that CO_2 and store the carbon in woody biomass. For perspective, Missouri's emissions of CO_2 (mostly from burning fossil fuels) are about 21 U.S. tons per person per year. If, for example, we wanted to offset all those emissions with equivalent forest growth and carbon storage, it would be necessary to increase Missouri's current annual rate of forest growth by roughly 900 percent.

We are fortunate to be able to work with forest ecosystems. They are the ultimate natural climate solution for regulating atmospheric CO_2, because they are genetically programmed to accumulate woody biomass via solar powered photosynthesis. Active forest management is critical to maintaining healthy, productive forests and can increase the amount of carbon stored in individual trees and in stands of trees through time. While working with forest ecosystems, it is important to not lose sight of the fact that most of the climate change problems associated with increased CO_2 emission are brought about by burning fossil fuels for energy and thereby releasing fossil carbon into the atmosphere. It is important to work on ways to reduce fossil carbon emissions while continuing to work on ways for forest ecosystems to mitigate unwanted consequences of the CO_2 already residing in the atmosphere.

Land ownership has important implications for management decisions. In Missouri, 82 percent of forest land—a total of 12.6 million acres—is in private ownership, with 359,000 private owners. The degree to which private owners will embrace carbon management for the purpose of reducing net output of greenhouse gases remains to be seen. The other 18 percent of Missouri forest land—2.8 million acres—are in public ownership. The majority of that acreage is covered by formal forest management plans. Usually, those forest plans are formulated with public input and address multiple objectives. National concerns about climate change and associated carbon emissions are so widespread it seems inevitable that forest carbon management will become a significant consideration in forest management decisions for public forest land in Missouri and elsewhere. Fortunately, many management activities and silvicultural practices that have traditionally been applied to increase output of wood products are also compatible with management for carbon sequestration and storage.

> "Carbon is the backbone of life on Earth. We are made of carbon, we eat carbon, and our civilizations—our economies, our homes, our means of transport—are built on carbon. We need carbon, but that need is also entwined with one of the most serious problems facing us today: global climate change.
>
> NASA Earth Observatory

1. Why are we concerned about carbon dioxide in the atmosphere?

The Earth's atmosphere is predominantly comprised of nitrogen (78 percent), oxygen (21 percent), and argon (1 percent). The 4th most common gas in the atmosphere is carbon dioxide (CO_2) at 0.0425 percent or 425 parts per million (as of March 2024) (NASA 2024a). Although CO_2 constitutes a small percentage of total atmospheric gases, it is essential to life on Earth and is an integral part of Earth processes including climate and carbon (C) cycles.

Atmospheric CO_2 gas is of particular interest due to its effect on the global climate. Carbon dioxide is a greenhouse gas. This means that CO_2 interacts with the atmosphere to trap heat in a manner conceptually similar to the way greenhouses trap heat and keep the greenhouse interior warmer than the outside air. Specifically, when sunlight penetrates the atmosphere, CO_2 and other greenhouse gases readily and repeatedly capture the heat and then dissipate it to other surrounding molecules in the atmosphere and on the Earth (PBS, 2023). This warms the atmosphere and the Earth, and the greater the concentration of CO_2 the more heat that is captured. Much of that heat is radiated back to space, but over time the climate gradually warms (NASA, 2024b). A warming climate has numerous consequences, many of which are undesirable.

Long-term monitoring shows the proportion of atmospheric CO_2 is increasing, largely due to human activities that burn fossil fuels (e.g., coal, petroleum, or natural gas formed by ancient geologic processes acting on decaying plants and animals). When burned, fossil fuels emit CO_2 into the atmosphere. Moreover, once CO_2 is emitted into the atmosphere, it remains there for centuries and continues to affect the climate (NASA, 2019). The Intergovernmental Panel on Climate Change (IPCC, 2024), the National Oceanic and Atmospheric Administration (NOAA, 2024), and the U.S. Department of Agriculture (USDA 2019 and 2024b) are among the many organizations that monitor past global atmospheric change and model future atmospheric change, particularly with respect to CO_2 and other greenhouse gases.

Carbon dioxide is not the only greenhouse gas in the atmosphere. Methane, for example, is much less common in the atmosphere than carbon dioxide, but methane is 28 times more potent in trapping and retaining heat (EPA 2023). Water vapor also acts as a greenhouse gas, and like carbon dioxide it contributes to the greenhouse effect (NASA 2022). As the climate warms, the atmosphere can hold more water vapor, and that accelerates the associated climate warming.

All earthly life forms are based on carbon, and they use carbon to build essential parts of their cellular structure. Trees and other photosynthetic plants are unique in the carbon cycle because they take up CO_2 from the atmosphere and water and nutrients from the soil in which they are growing. Through photosynthesis, which is powered by sunlight, trees and other plants create carbon-based sugar molecules (carbohydrates comprised of hydrogen, oxygen, and carbon), and they release oxygen (O_2) back to the atmosphere. Trees use carbohydrate molecules to build wood and other tree tissues. Thus, as a tree grows it draws more CO_2 from the atmosphere and stores the carbon in the wood of the tree (Figure 1). In the simplest terms, photosynthesis turns carbon dioxide into wood.

See the Glossary near the end of this document for definitions of technical terms.

Figure 1. The forest carbon cycle. Through photosynthesis trees take up atmospheric carbon dioxide and convert it to woody biomass, which is about 50 percent carbon. This reduces the quantity of carbon dioxide in the atmosphere. As trees grow, their biomass (and stored carbon) accumulates in tree boles, branches, and roots. Over time, carbon also accumulates in soil and forest floor litter. Periodically, trees may be harvested, and some of their stored carbon is converted to wood products or biofuels. When trees die and decompose, their stored carbon is emitted back into the atmosphere as carbon dioxide, completing the cycle. (Kosiba, 2023; illustration by Erick Ingraham; used with permission).

Trees are large, long-lived, and widely dispersed. Over time, they can sequester and store large quantities of carbon in wood while they simultaneously provide numerous other benefits to people and the environment. Wood products and forest disturbances are essential parts of the forest carbon cycle (Figure 2). Dead trees become sources of carbon dioxide. They release their stored carbon back into the atmosphere as CO_2 through decomposition or combustion in the case of fires. Trees and forests are of special significance in mitigating undesirable consequences of climate change, because carbon sequestration in trees and forests helps offset carbon emissions associated with burning fossil fuels.

The impacts of increased greenhouse gases in the atmosphere are complex. Greenhouse gases do not uniformly increase the Earth's temperature. Temperature changes are affected by latitude and longitude, topography, landcover, and human activities, among other factors. Temperature changes affect patterns of precipitation, vegetation growth, vegetation reproduction, human and animal health, food supply, and transportation. Geographically the impacts of climate change are frequently observed in proximity to edges of ecoregions (e.g., along the transition from temperate hardwood forests to boreal forests).

Models of global climate change indicate that the climate impacts of atmospheric CO_2 and associated greenhouse gases will accelerate unless humans are able to greatly reduce emissions of greenhouse gases and/or develop the capacity to capture greenhouses gases from the atmosphere and store them. Such actions are difficult to implement due to their global reach and the complex social, economic, political, technological, and environmental factors that come into consideration.

Note that atmospheric changes in CO_2 and associated climate change are global phenomena. In the long run, it doesn't much matter where greenhouse gases enter the atmosphere. Once emitted, they gradually get mixed into the global atmosphere where they have a global impact on climate. Global climate trends affect the climate in Missouri and everywhere else. However, within and around Missouri we have the capacity to take actions that reduce the rate at which greenhouse gases are emitted into the atmosphere. Moreover,

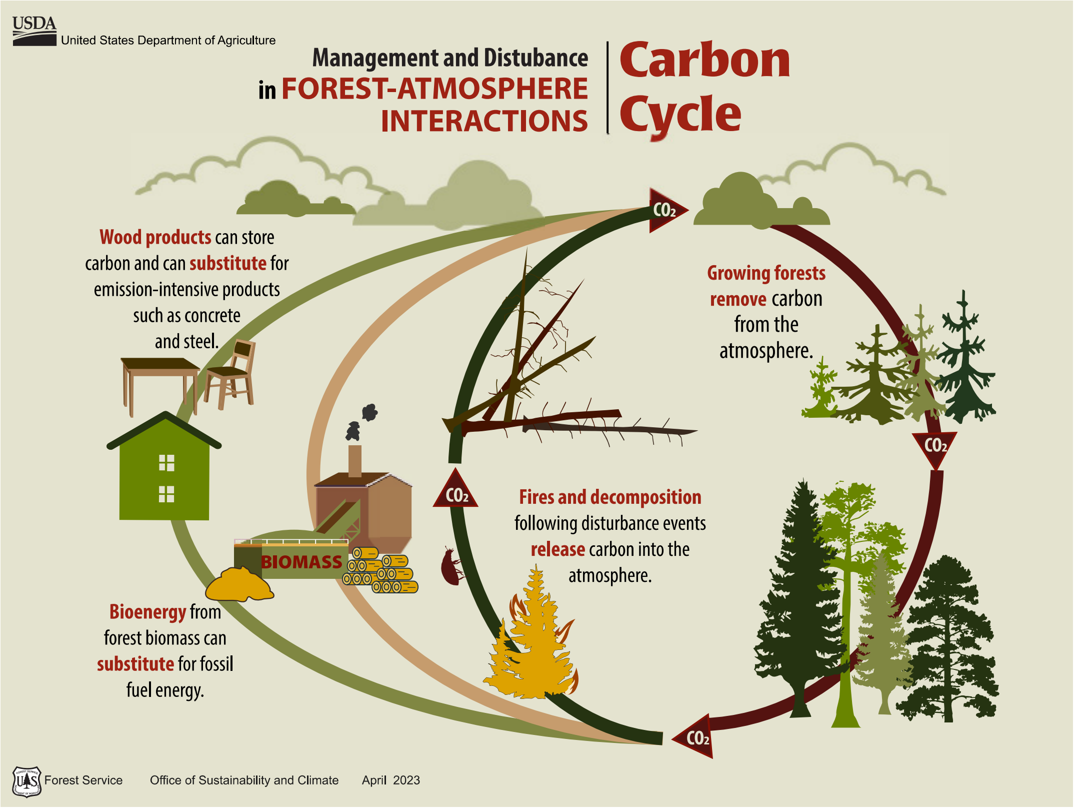

Figure 2. Pathways of forest and carbon interactions in the presence of landscape disturbances. Through photosynthesis, trees take up CO_2 from the atmosphere and sequester the carbon in wood and other tree tissues. That carbon is stored until disturbances, such as insects or fire, kill some of the trees and release their carbon back into the atmosphere as CO_2 that can be used by new trees. Other trees are utilized to produce wood products that can store CO_2 for decades or are utilized for bioenergy which can substitute for energy produced from fossil fuels. What is not shown in this illustration are the massive additions of CO_2 to the atmosphere caused by burning fossil fuels. (Figure 9 in Section 6 illustrates forest carbon pathways in greater detail.) Source: U.S. Forest Service

through thoughtful management of forest ecosystems we can increase the capacity of forests to pull CO_2 from the atmosphere via photosynthesis and store the carbon in live trees, forest soils, and durable wood products. The processes of carbon sequestration and storage in forest ecosystems can partially offset the quantity of carbon emitted by using fossil fuels for transportation, electricity generation, and industry.

> ***Trees are without a doubt the best carbon capture technology in the world.***
>
> Calvin Norman and Melissa Kreye, PennState Extension

2. Basics of biomass and carbon in trees

The tissues of trees or other plants are called biomass. The total biomass of a tree includes the weight of its bole, branches, leaves, and roots. For discussion and analyses it is common to separate biomass into components such as above-ground, below-ground, living, dead, boles, branches, coarse roots, or fine roots. For large trees, components such as the biomass of roots are difficult to measure directly because doing so requires excavating a tree's roots, washing them, drying them, and weighing them. Consequently, biomass measurement is usually focused on tree boles. Bole biomass is a good indicator of total biomass. By the time a tree reaches 5 inches dbh, the majority of its biomass (and carbon) is typically contained in the tree bole.

Much is already known about how to estimate the volume and mass of tree boles. The other components of biomass are often estimated as a proportion of the bole biomass or of the total tree biomass. Biomass equations range in complexity from simple equations that estimate above-ground tree biomass to sophisticated systems of equations that estimate above-ground and below-ground biomass by tree component (roots, boles, branches). The following references illustrate a range of biomass equations: Smith, (1985); Jenkins et al. (2003, 2004); Miles et al. (2009); Woodall et al. (2011); Westfall et al. (2023).

For those familiar with computation of tree basal area, it is useful to understand that tree basal area is highly correlated with tree biomass. Basal area and biomass are both computed as a function of a tree's diameter.

Living and dead trees contain moisture, and the weight of a tree varies with the amount of moisture it contains. A tree's moisture content varies with its species, size, whether live or dead, whether standing or down, and by the available soil moisture. To make useful comparisons of biomass among trees that may have different percent moisture content, biomass estimates are usually converted to and reported as the biomass dry weight. Dry weight is the weight of the tree or tree components when they are dried to zero percent moisture content. Experimentally the moisture content of a wood sample can be determined by measuring the weight of the sample when freshly cut, then placing the sample in an oven and measuring the declining weight of the sample over time until the sample weight is no longer decreases (i.e., the moisture is gone, and the sample is at oven-dry weight). Fortunately, equations are available to estimate tree biomass dry weight based on a tree's species and dbh (Figure 3).

In general, the greater a tree's diameter, the greater its basal area, the greater its biomass, the greater its dry weight, and the greater the carbon stored in the tree. The woody biomass in a tree is largely comprised of carbon-based organic compounds (ACS 2009). Thus, woody biomass is a reservoir of carbon. In fact, about half the dry weight of the bole of an oak tree in Missouri (or elsewhere) is carbon (Lamlom and Savidge, 2003).

GUIDELINES FOR INTERPRETING INFORMATION ABOUT FOREST-ASSOCIATED CARBON

In discussions and comparisons of forest carbon data, the key is to remain cognizant of which measure of carbon is being reported (i.e. CO_2 gas or solid carbon), over what timeframe, and for what geographic area. It is also important to remain cognizant of the measurement units that are used to report carbon and CO_2 values. Traditionally, forest measurements in the U.S. are reported in English units (inches, feet, miles, pounds, tons, Fahrenheit). However, carbon and climate metrics are of global interest and reported almost exclusively in metric units (centimeters, meters, kilometers, kilograms, metric tons, centigrade). To avoid confusion, read the fine print in tables, figures, and text.

Although they are related, the quantity of carbon stored in trees is tracked and reported differently than the carbon in the atmosphere. Carbon in trees refers to the amount of carbon in the molecules that make up the wood and other tissues that form the tree. The amount of carbon stored in a tree, for example, is almost always reported as the dry weight (mass) of solid carbon (C). As a general guideline, the amount of carbon stored in a tree, or in a stack of lumber is half the dry weight of the wood.

In contrast, carbon in the atmosphere occurs not as a solid, but as CO_2 gas; one carbon atom joined with two oxygen atoms. Thus, a ton of CO_2 gas (with carbon and oxygen bound together) has less than a ton of carbon. To convert a quantity of carbon in a tree to the corresponding quantity of carbon dioxide, multiply the carbon mass by 3.67. To convert a quantity of carbon dioxide to the equivalent quantity of carbon, divide the carbon dioxide mass by 3.67 (i.e. one metric ton of CO_2 contains 0.27 metric tons of actual carbon; the rest is oxygen).

Sometimes greenhouse gas emissions are reported as carbon dioxide equivalent (CO_2 equivalent or CO_2e). This is done to report the combined impact of multiple greenhouse gases together, such as CO_2 plus methane; given that a molecule of methane is 28 times more potent as a greenhouse gas than a molecule of CO_2.

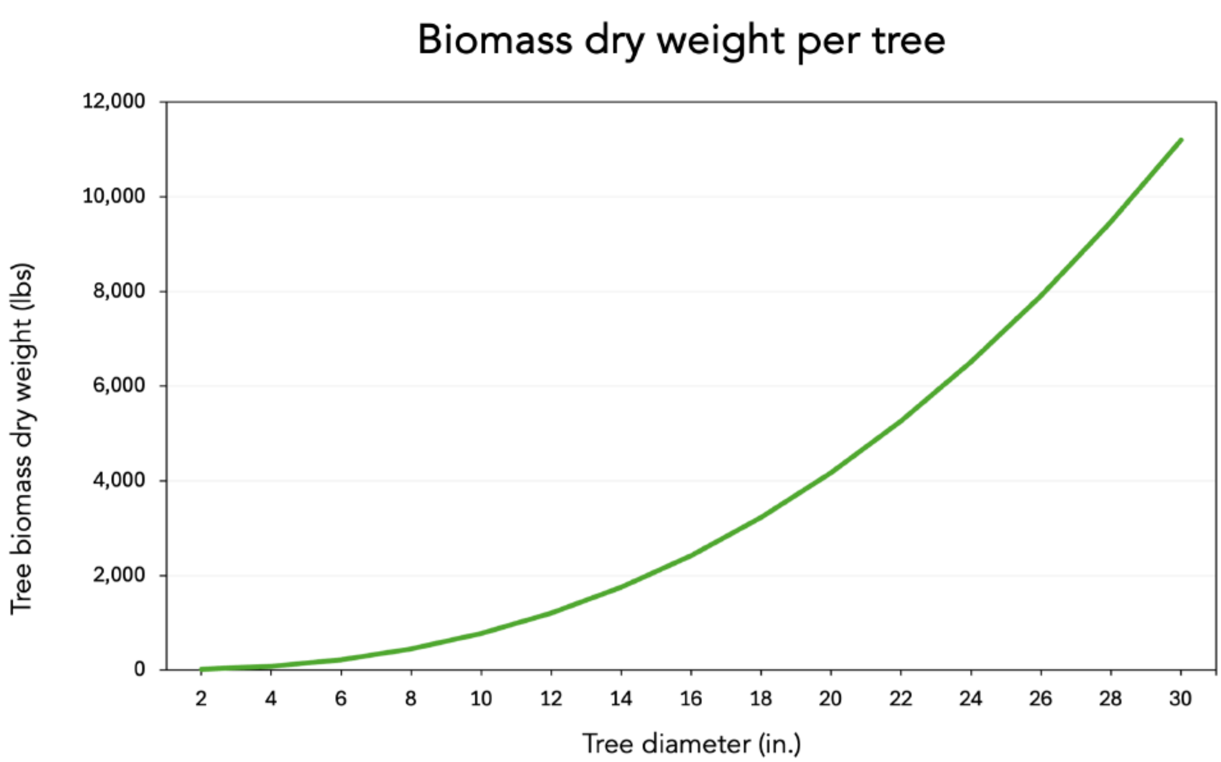

Figure 3. Change in above ground live tree biomass by tree dbh for oak, hickory, beech, and hard maple trees. The quantity of carbon sequestered in each tree is approximately half the dry weight of the biomass. (Jenkins et al., 2003).

> ***Human activities are responsible for almost all of the increase in greenhouse gases in the atmosphere over the last 150 years.***
>
> U.S. Environmental Protection Agency, 2023

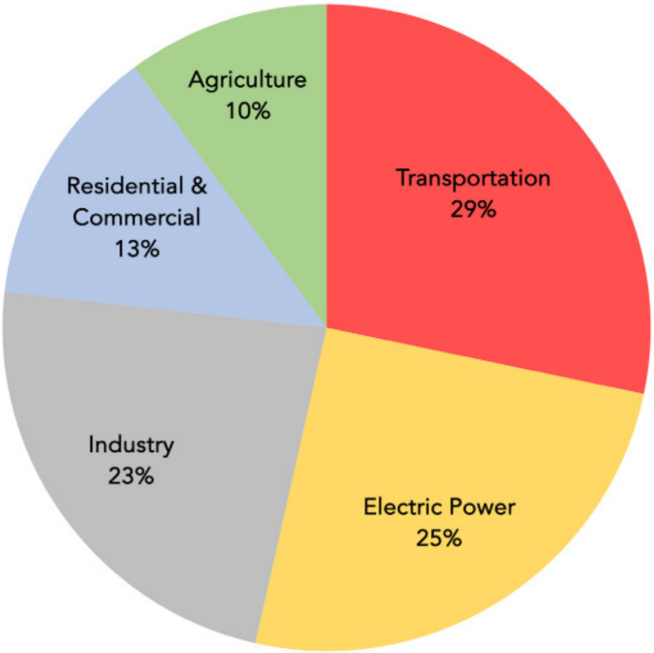

Figure 4. Carbon dioxide emissions (percent) by economic sector, 2022. Total U.S. emissions exceed 6 billion metric tons of CO_2 equivalent (CO_2e). Per capita annual U.S. emissions are approximately 18 metric tons of CO_2e. (EPA, 2024a; EPA, 2024d; World Bank, 2024).

3. How much carbon are we talking about?

Missouri forests cover 15.4 million acres or 35 percent of all Missouri land. The total woody biomass on Missouri forestland is approximately 671 million dry tons. Half the biomass (or 335 million dry tons) is stored carbon (C). The per capita stored carbon for Missouri's 6.2 million residents is about 54 dry tons (Oswalt et al., 2019 Table 38a).

Fifty-four tons of stored carbon for each Missouri resident sounds like a large stockpile. Moreover, as forests grow and increase in biomass, they sequester additional carbon. However, every year human enterprises emit large quantities of carbon dioxide into the atmosphere by burning fossil fuels for transportation, manufacturing, energy generation, and other activities (Figure 4).

Forests sequester more carbon from the atmosphere than they require for their own growth and respiration, so forests are carbon sinks (accumulators of carbon). Consequently, forestry is not included as a category of carbon emissions in Figure 4. Nationally, growth of forests plus the accumulation of harvested wood products annually sequester and store the equivalent of 14 percent of total U.S. CO_2 emissions. For all greenhouse gases combined (CO_2 plus methane, nitrous oxide, and florinated gases), U.S. forest-associated carbon sequestration and storage amounts to about 11 percent of annual emissions. On average, U.S. forests sequester 0.6 metric tons of carbon per hectare per year (535 U.S. pounds of carbon per acre per year) (Domke et al., 2021).

For those interested in knowing the source of those 18 metric tons of carbon emitted per capita, there are online "Carbon Footprint" calculators to help estimate the carbon impact associated with one's choices in transportation, heating, cooling, and more (e.g., Carbon Footprint Calculator | Climate Change | EPA, 2016).

Most often when we are discussing forest carbon, we are focused on the carbon in living trees. However, forest soils are also of great importance. Globally, forest ecosystems store more than twice as much carbon in forest soils than in aboveground biomass (Kosiba, 2023; D'Amore and Kane, 2016). In Missouri, however, the quantity of carbon in forest soils is roughly equal to aboveground carbon in trees and other vegetation. This is due to the characteristics of the Missouri soils, particularly in the Missouri Ozarks, which are poorly suited to accumulation of organic matter.

CARBON EMISSIONS VS. SEQUESTRATION IN MISSOURI

Annual CO_2 emissions from the use of fossil fuels far exceed the quantity of atmospheric CO_2 that is annually sequestered and stored as carbon in forests, in the oceans, or in any other form (EPA, 2024c).

Missouri annual CO_2 gas emissions are equivalent to 19 metric tons per capita, slightly more than the U.S. average. Those greenhouse gas emissions contribute directly to climate change.

Theoretically, the climate impact of Missouri CO_2 emissions could be offset through photosynthesis if Missouri forests were able to sequester and store enough carbon in tree biomass to match annual CO_2 emissions. Doing that would require 10 metric tons of biomass growth per person per year. Collectively for Missourians, that amounts to a total of 62 million cubic feet of biomass growth per year.

That quantity of annual biomass growth is 9 times greater than the current rate of biomass growth for Missouri forests. So if Missouri forests were to accumulate enough woody biomass to offset Missouri's annual fossil fuel emissions, forests would need to be growing at about nine times their current rate. Or alternatively, we could reduce our use of fossil fuels by 89 percent. Neither option is currently a plausible solution.

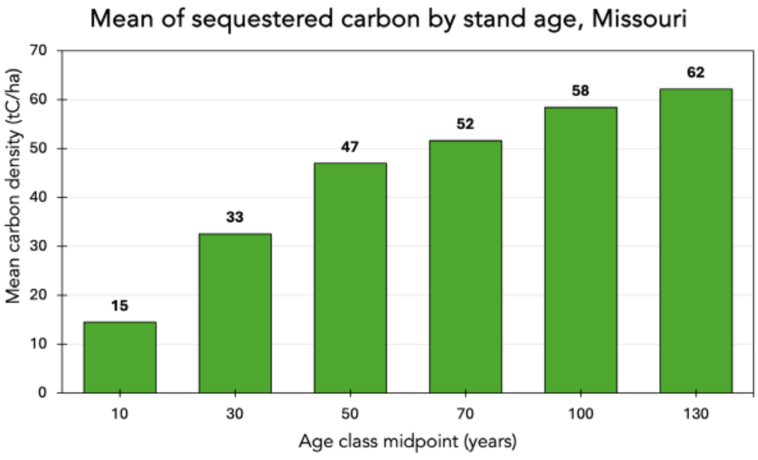

Figure 5. Mean of stored carbon (metric tons of C per hectare) in the above-ground portion of live trees in forest stands in Missouri. (Hoover and Smith 2023a, Supplemental Table S4).

You will die but the carbon will not; its career does not end with you. It will return to the soil, and there a plant may take it up again in time, sending it once more on a cycle of plant and animal life.

Jacob Bronowski,
mathematician and philosopher

4. Carbon dynamics in forest stands

A forest stand is a spatially contiguous management unit comprised of trees of reasonably similar age, species composition, and structure, existing in a place with reasonably similar site conditions. Stands are typically 10 to 100 acres in spatial extent, and most forest management activities, including tree harvesting, are planned and implemented on a stand basis. Thus, it is important to understand how stand-scale carbon sequestration and emissions change over time as stands age without disturbances and with disturbances, including stand management activities.

We saw previously that the amount of carbon stored in a living tree is typically estimated as half the dry weight of the tree's biomass. Tree biomass and tree carbon increase with tree size. Trees that die or are cut and left to decay will gradually decompose and release their stored carbon back into the atmosphere as carbon dioxide.

Research by Hoover and Smith (2021, 2023a; 2023b) analyzed observations for tens of thousands of forest inventory plots that had been installed and remeasured by the USDA Forest Service, Forest Inventory and Analysis (FIA) group. One of the many variables those forest inventory plots estimate is the mean amount of carbon sequestered per hectare, by region, by forest-type group, and/or by age class (Figure 5).

Figure 5 is an important graphic illustrating how carbon accumulates over time in forest stands in Missouri. After a stand-initiating disturbance (e.g., when a new stand is established following harvest, wildfire, insect damage, weather damage, and/or disease) the regenerating trees (in the 10-year age class in Figure 5), typically have ample growing space and grow rapidly. Via photosynthesis the trees sequester and store carbon as they increase in size. Rapid increases in wood volume, biomass, and stored carbon continue through age class 50 as shown by large increments in stored carbon among age classes 10, 30, and 50 years. After age class 50, the increase in stored carbon between age classes gradually diminishes.

The values reported in Figure 5 are what would be called a "woods-run average". They reflect average values for stands of a given age class, including stands that may have experienced past partial disturbances. Consequently, reported values are lower than would be expected for stands that had never been disturbed.

Managers are interested in knowing the upper limits of stored carbon per hectare. Old-growth forests, although rare in Missouri, give insight to the maximum biomass and carbon that can be stored per hectare. Fraser et al. (2023) inventoried the quantity of above-ground carbon in ten undisturbed old-growth hardwood stands in Missouri, Illinois, and Indiana. The mean quantity of stored carbon in these stands was 125 metric tons of carbon per hectare (125 tC/ha) in 1990, and it increased to 134 tC/ha by 2010. The stored carbon for the old-growth sites was about twice the quantity for the 130-year age class in the state-wide inventory by Hoover and Smith (2023a) (Figure 5). The annual increase in carbon for the old-growth sites was about 0.5 tC/ha/year. This equated to a 0.5 percent annual increase. This pattern is consistent with the findings of Birdsey et al. (2023) and others (Moomaw et al., 2019) who concluded that if temperate forests in the eastern U.S. are undisturbed, they can continue to accumulate carbon for many decades, but at a declining annual rate.

This general pattern of biomass accumulation is common in tree and stand growth. A newly regenerated stand begins to accumulate carbon, biomass, and cubic foot volume as it grows. As the stand ages, competition intensifies among the trees in the stand. Trees compete for growing space, and poorly adapted trees are crowded out by competitors. Well-adapted trees continue to increase in size (and in the magnitude of sequestered carbon, biomass, volume, and basal area). As the stand increases in stocking and age, it gradually approaches the carrying capacity of the site. Additional increases in stand biomass or stored carbon by well-adapted trees are generally offset by death of other trees in the stand. This

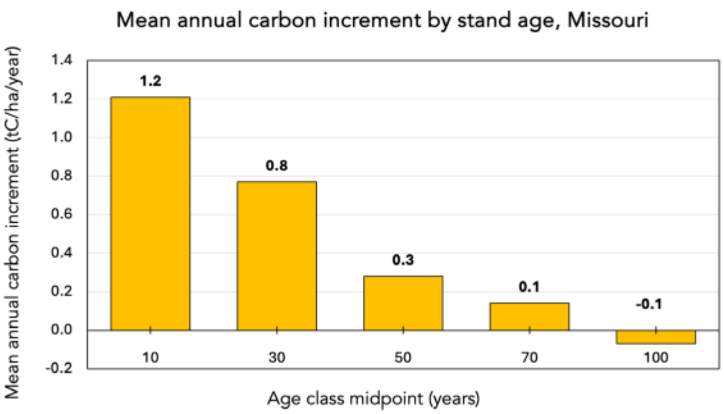

Figure 6. Mean annual rate of sequestered carbon accumulation in metric tons per hectare per year (tC/ha/yr) in the above-ground portion of live trees in forest stands in Missouri. (Hoover and Smith 2023a, Supplemental Table S5).

can result in fluctuations over time in biomass or carbon per hectare, but the general pattern is that the net rate of annual carbon accumulation gradually declines and approaches zero with increasing age of forest stands (Johnson et al. 2019; Gingrich 1971).

As a management protocol, keeping a forest stand protected from disturbance and allowing the trees in the stand to increase in size will allow the stand over decades to accumulate a relatively large quantity of stored carbon. However, as illustrated in Figure 6, the annual rate of carbon accumulation declines with increasing stand age and approaches zero for the oldest age classes.

Figures 5 and 6 are two views of the same pattern of forest dynamics. Figure 5 shows an estimate of the *total accumulated carbon per hectare* for Missouri oak stands by age class. Figure 6 highlights the *annual rate of carbon accumulation per hectare* by age class in Missouri oak stands.

The annual rate of carbon accumulation declines with increasing age. The fastest rate of carbon accumulation (1.2 metric tons of carbon per hectare per year) was reported for the 10-year age class (Figure 6). The annual rate of carbon increment clearly declines with increasing stand age. For stands that reach the 70-year age class the mean annual rate of carbon accumulation has declined twelve-fold to 0.1 metric ton of carbon per hectare. For stands in the 100+ year age class the estimated mean annual rate of carbon accumulation per hectare is -0.1 metric tons. That is indicative of a mean annual loss of above-ground live carbon. That would typically occur in stands where live trees died, and the associated carbon was shifted from the category of live tree carbon to the category of dead tree carbon. Dead trees or tree parts continue to store carbon for a period of time, but as they decay their carbon is released back into the atmosphere as CO_2. Whereas live trees in the stand continue to accumulate and sequester carbon (i.e., are a carbon sink), dead trees release carbon into the atmosphere (i.e. become an atmospheric carbon source).

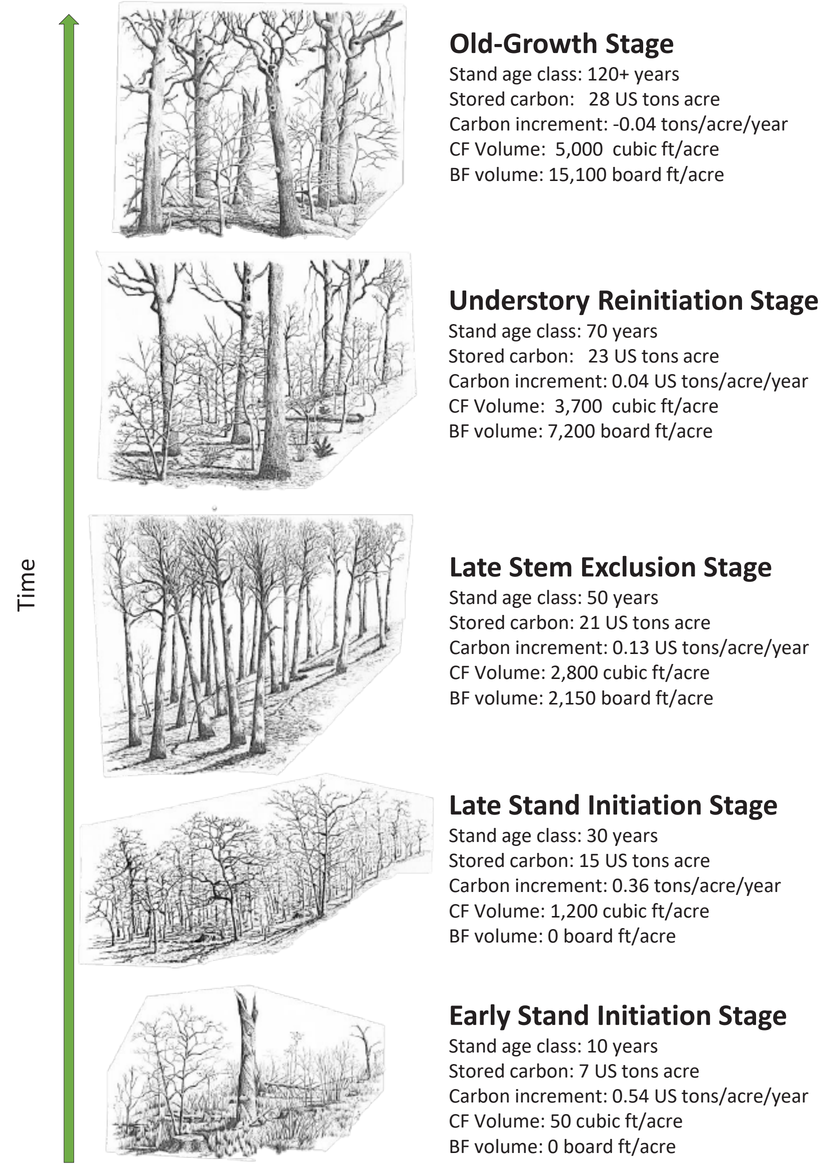

Figure 7. The structural stages of forest stand development on the Ozark Plateau. Information for each stage includes representative values for stand age, stored carbon, annual rate of carbon increment, cubic-foot (CF) volume, and board-foot (BF) volume. Stand descriptions are from Evans and Kirkman (1981) which includes these Illustrations drawn by D.A. Hamilton. Estimates for carbon storage and carbon increment are Missouri averages across all forest land as reported by Hoover and Smith (2023a) converted to English units of measurement. Cubic and board foot volumes are estimates based on fully stocked undisturbed oak stands with site index 65 as reported by Gingrich (1971) and Schnur (1937). Volume and stored carbon increase with increasing stand age; annual carbon increment decreases with increasing stand age.

Stands with large quantities of live biomass and the associated stored carbon (old stands in this case) are at some risk of losing their stored carbon through forest disturbances. Insects, diseases, severe weather and fires can quickly turn carbon stored in live trees to carbon in dead trees that, through decay, emit their CO_2 back to the atmosphere. If lost through a stand-scale disturbance, stored carbon in biomass that may have accumulated over many decades (e.g., Figure 5) will take many decades to replace. Thus, attention to forest health and protection is an essential part of managing stored carbon.

Harvesting is also a forest disturbance that affects carbon storage. Unlike the unwanted disturbances and carbon losses resulting from insects, disease, weather and wildfires, harvesting is controlled by forest managers and the harvested carbon in a tree or stand is not necessarily released into the atmosphere by decay. Later sections discuss risk management and how the carbon in harvested trees can still be stored in wood products. It is not only the quantity of stored carbon that changes with stand age. Forest structure, species composition, wildlife habitat suitability, aesthetics, and product volumes all change over time (Figure 7).

There is nothing so stable as change.

Bob Dylan,
poet and musician

5. Landscape-scale forest carbon management considerations

Together the patterns of total carbon accumulation by age class and annual rates of carbon accumulation (Figures 5 and 6) present a conundrum for those interested in managing forests to sequester and store carbon at the landscape scale. It is impossible to (a) simultaneously maximize the annual rate of carbon accumulation that was observed among the youngest stands in Figure 6, and (b) maximize the total accumulated quantity of stored carbon observed among the oldest stands shown in Figure 5.

Persistent management for old forest conditions could theoretically result in a forest landscape populated only by old forests, and with maximum stored biomass and carbon in living trees. However, when aging stands accumulate carbon at or near maximum carrying capacity, little or no additional net carbon can be sequestered by those forests in subsequent decades. The forest carbon sink (i.e. capacity to sequester additional carbon) is saturated for these stands until a major disturbance creates some new, young stands. An old forest stand may have sequestered and stored carbon continuously for a century or more, but the older it gets the less additional carbon it can sequester. Alternatively, persistent management for rapid annual growth of forest stands would theoretically require that a stand's total carbon stock be kept below maximum, allowing relatively rapid stand growth resulting from the available growing space associated with younger stand ages and lower carbon stocks.

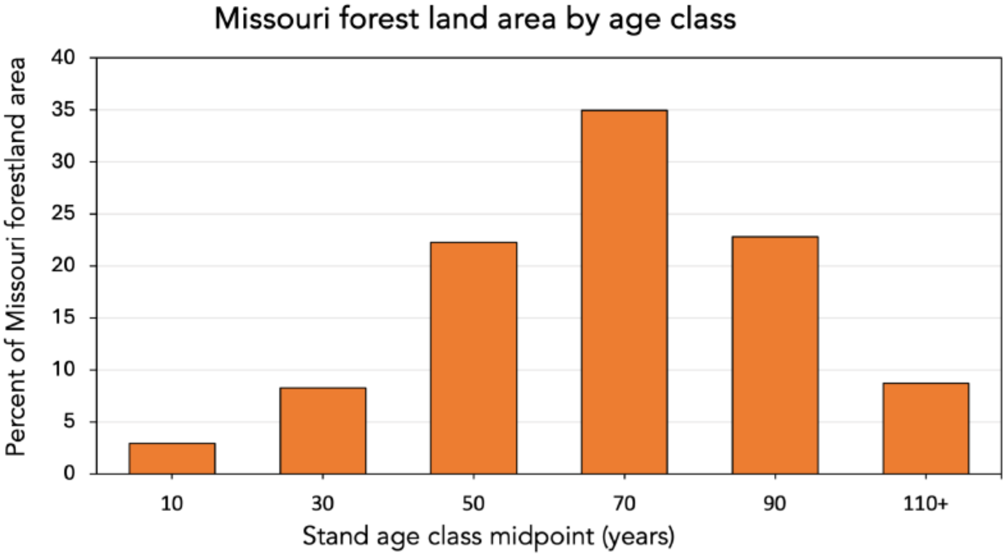

Figure 8. Proportion of Missouri forest land area by age class. The total forest land area is 15.4 million acres. The mean stand age is 70 years. Missouri forests are aging, and the majority are lightly disturbed. Although Missouri forests have sequestered and stored large quantities of carbon, the consequence is that the rate at which carbon is sequestered in future decades will decrease (USDA Forest Service, Forest Inventory and Analysis Program, 2024a).

The existing forests in Missouri are already relatively old (Figure 8). In the absence of forest management or large-scale, stand-initiating disturbances, the tendency will be for existing stands in Missouri to continue to age over the next several decades and gradually accumulate relatively large carbon stocks (Domke, et al., 2021). As that happens, the annual rate of carbon sequestration by Missouri forests will decline. Consequently, the total amount of carbon stored in Missouri forests will remain static or decline. This outcome is sometimes termed saturation of the forest carbon sink, because old forests with large carbon stocks (carbon sinks) have little capacity to sequester additional carbon. From a forest management perspective, what is more important, having a faster rate of carbon sequestration per year but a lower total carbon accumulation, or having greater total carbon accumulation now but with little future capacity to annually accumulate additional carbon?

Given the multiple objectives and the complex considerations associated with virtually all contemporary forest management plans, it is hard to conceive of a situation that would heavily favor a large landscape with a young forest age distribution, low carbon stocks, and rapid annual carbon increment, nor one that would heavily favor old forests that would have accumulated large carbon stocks with saturated carbon sinks and little or no ongoing annual carbon increment. Moreover, managing forests for the sole objective of maximizing either stored carbon or the rate of carbon sequestration is unlikely to create and maintain forest structure, composition, and functions associated with other management objectives related to wildlife habitat, conservation of biodiversity, forest health concerns, recreation, and commodity production. However, managing for healthy and vibrant forests can accomplish multiple objectives that include carbon accumulation, and understanding how forest management affects carbon dynamics can lead to better informed management decisions.

Managing forests for carbon and biodiversity has many benefits. It can improve the resilience of forests and communities, while continuing to provide sustainable economic opportunities and climate-friendly products to market.

Laura Smith, Nature United

The following sections discuss the capacity of forest management practices to alter the rate of carbon sequestration and the quantity of stored carbon, the role of durable wood products in carbon storage, and the capacity to substitute wood with its stored carbon for products such as steel or cement that require large quantities of fossil fuel to produce.

6. Stand management practices that increase the quantity of carbon that is sequestered and stored

Land and vegetation management practices that increase carbon storage and/or decrease greenhouse gas emissions fall into the category of "Natural Climate Solutions" (Griscom et al., 2017). Natural Climate Solutions are not limited to forest ecosystems, but forests are highly amenable to their implementation. Natural Climate Solutions rely on Earth's natural ecological processes (e.g., photosynthesis) as drivers of carbon sequestration and storage; this differentiates these natural processes from technological and engineering solutions to reduce atmospheric CO_2.

There are three general categories of Natural Climate Solutions related to forest management: (1) replacing forests, (2) reducing risk of loss, and (3) managing to increase stored carbon.

The category of replacing forests includes the silvicultural practices of afforestation and reforestation. Afforestation–converting non-forest land to forest cover–typically increases a site's long-term carbon storage relative to alternative land cover and land use options (e.g., agriculture or residential land use). Reforestation of previously forested stands (e.g., stands that experienced a disturbance that removed the overstory trees) resets a stand's trajectory of carbon storage. The efficacy of reforestation in increasing stored carbon depends in part on what happened to the carbon that was previously on the site and the rate

MANAGING THE RISK OF CARBON LOSS

Forest health issues can rapidly convert carbon stored in forest biomass into atmospheric CO_2 through mortality and decomposition. In Missouri, oak decline has been a concern over the past few decades. It occurs when apparently healthy oak trees experience relatively rapid decline in vigor that results in tree death. It is commonly observed among species in the red oak group, such as black oak (*Q. velutina*) and scarlet oak (*Q. coccinea*), which are two very common species in upland forests of Missouri. Considerable research has gone towards understanding the factors affecting oak decline. It is associated with a complex variety of interacting environmental stressors, including poor quality sites, drought events, root fungi, and stands with high stocking. Taken together, these factors reduce the longevity of red oak species in the region to around 70-90 years.

Given the history of Missouri forests, the landscape is dominated by stands that are around 70 years old, with a high proportion of red oak species on upland sites. As stands have entered this age class over the past few decades, red oak mortality has been widespread. Mortality without management results in stands with excessive standing dead trees, releasing carbon back into the atmosphere through decomposition. While these stands are expected to recapture carbon through regeneration, the rate of reforestation and the resulting composition and structure is less predictable than following regeneration harvest.

Forest management can reduce the negative impacts of oak decline. However, the ability of forest management to directly prevent oak decline appears limited. While there is some evidence that maintaining stand density below overstocked conditions can reduce the prevalence of oak decline, the longevity of species in the red oak group can be expected to be 70-90 years regardless of stand density. By anticipating this, forest managers can develop silvicultural prescriptions that harvest red oak species prior to mortality. This provides opportunity to continue to store the carbon from these trees as wood products rather than releasing it back into the atmosphere through decomposition. In addition, managers can decide the most appropriate silvicultural prescription for the stand to reach future objectives of reforestation if regeneration is needed or thinning if the residual stand can meet management objectives.

at which the reforested site accumulates carbon in the future. Implementation of afforestation or reforestation provides an opportunity to favor tree species best suited to future climate conditions. Forests store more carbon than other terrestrial land types, so efforts to retain or expand forest cover are beneficial for increasing carbon storage at stand and landscape scales.

When managing stands for the purpose of sequestering and storing carbon, it is fundamental to protect existing forest stands and reduce the risk of carbon loss through tree mortality. When a tree dies, photosynthesis stops and the tree begins to decay. As it decays it gradually emits its carbon back to the atmosphere in the form of carbon dioxide. The dead tree transitions from being a carbon sink (accumulator) to a carbon source (emitter). Whether or not an entire stand transitions from a carbon sink to a carbon source depends on the number and size of trees affected by mortality events.

When trees are burned, they quickly release their stored carbon back into the atmosphere in the form of carbon dioxide. The greater the quantity of biomass consumed by the fire, the greater the quantity of carbon dioxide emitted. Generally, practices that reduce the extent and intensity of wildfires will aid in keeping a stand's stored carbon intact. However, managing fire risk is complicated. Wildfires have a random element in when and where they occur. Moreover, prescribed fires may be specifically designed to trade a stand's sequestered carbon for benefits of prescribed burning such as greater vegetation biodiversity or improved tree regeneration success.

Thoughtful selection of silvicultural systems applied to forest stands can simultaneously increase carbon sequestration and output of forest products. Thinning forest stands is a common intermediate treatment used to increase the yield of forests managed for merchantable timber. Thinning removes some of the trees in a stand, and in doing so provides more moisture, nutrients, and growing space for the residual trees. There are many protocols for thinning stands. These include thinning from above (primarily removing trees from the upper canopy), thinning the midstory (primarily removing trees from the midstory), and thinning from below (primarily removing trees from the lower canopy layers. Provided thinned stands are maintained in a fully stocked condition as described by Gingrich (1967) and Rogers (1983), the periodic thinning treatments provide opportunities to favor future growth of vigorous trees of desirable species. The trees that are removed in the thinning process can be converted to forest products that continue to sequester carbon.

Hoover and Stout (2007) reported on a 25-year study of the carbon dynamics and product output for Allegheny Hardwood forests managed with silviculture treatments of thinning from above, thinning from the midstory, thinning from below, and a no-harvest control treatment. The greatest rate of mean annual carbon accumulation came from the thin-from-below treatment and the no-harvest control, which were statistically the same and greater than observed for the treatments thinning from above and thinning from the midstory. Carbon estimates included the quantity of above-ground carbon and the annual rate of carbon increment for all live trees plus the estimated carbon in the merchantable board feet of timber produced by the alternative thinning treatments.

Looking specifically at the merchantable volume of wood (rather than the carbon) associated with the thinning treatments, Hoover and Stout found that the rank of the treatments in producing merchantable board feet from greatest to least was thinning from below, no-thin control, thinning from the midstory, and thinning from above. This ranking was identical to the ranking for total carbon sequestration and storage. Hoover and Stout found no significant difference between the treatment of thin from below and the control treatment. However, both those treatments produced significantly greater merchantable volume and stored carbon than the other thinning treatments.

Research by Anderson et al. (2023) examined the impact of stand density management practices on carbon sequestration in upland mixed oak forests and in shortleaf pine forests growing in the Missouri Ozarks. For unthinned pine stands, above-ground carbon stored in live trees peaked at age 50 with approximately 100 metric tons per hectare. Above-ground live carbon in unthinned upland oak stands also peaked at 100 metric tons per hectare but at stand age 80 rather than 50 as was observed for pines.

The impacts of thinning treatments on carbon sequestration observed by Anderson et al. (2023) were generally consistent with findings of Hoover and Stout (2007). Unthinned stands maintained the greatest live, above-ground carbon at any given point in time. However, for thinning treatments that maintained the residual stand in a fully stocked condition, the cumulative carbon storage for thinned stands, including carbon associated with trees that were removed for forest products, exceeded that for unthinned stands. Thus, stand thinning practices that retain and favor vigorous trees of desirable species and produce forest products can provide carbon sequestration benefits that reach or exceed those associated with stands receiving no harvest.

If harvested trees are manufactured into forest products, those products continue to store carbon for their useful life—often for many decades. Later sections of this report address the carbon storage benefits associated with utilization of wood products.

Those who work with forests and forests products are in the business of managing, growing, harvesting, selling and moving carbon. Wood is carbon. We call it by other more specific names, and we turn it into products, but wood is carbon.

Steve Shifley, Forester,
University of Missouri

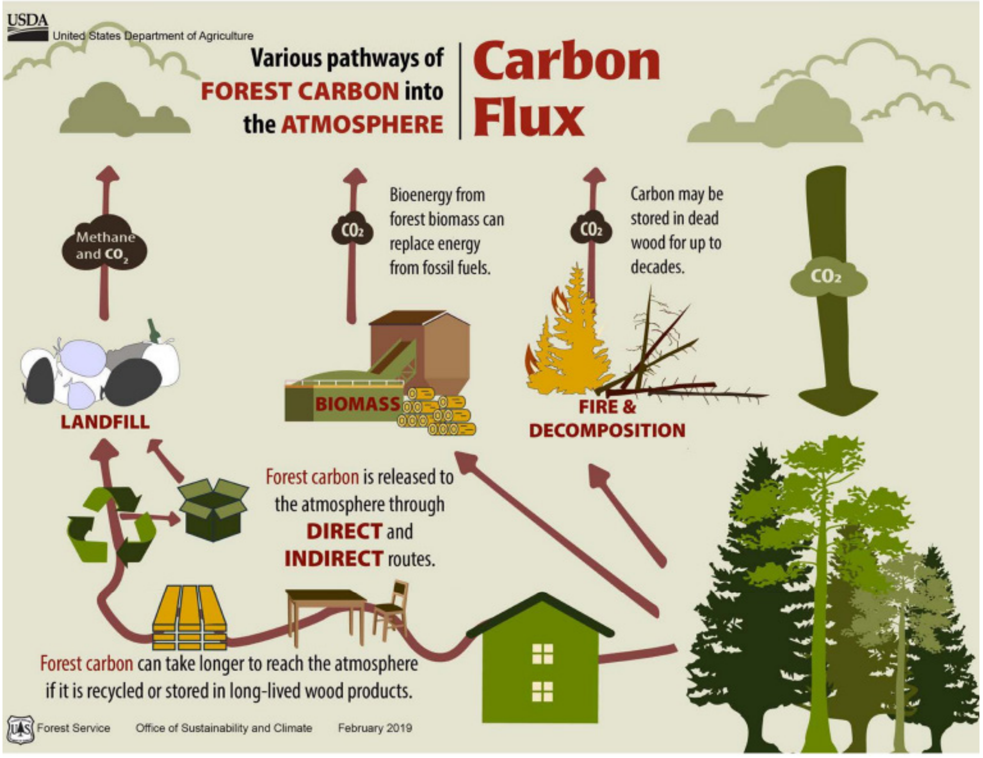

Figure 9. Creating wood products and utilizing biomass for energy are pathways that can increase carbon storage and reduce carbon emissions from fossil fuels. Source: US Department of Agriculture (https://www.fs.usda.gov/managing-land/sustainability-and-climate/carbon)

7. Carbon storage in wood products

Generating wood products is widely recognized as a management practice for increasing the quantity of stored carbon (Malmsheimer et al. 2011; Bowyer et al. 2011a.; Bowyer 2011b). Consider the case of a mature, fully stocked forest stand in Missouri. Over prior decades, it will have sequestered and stored a large quantity of carbon in live trees. If some of those trees were harvested and processed into durable wood products such as flooring, cabinetry, or structural panels, the carbon in those wood products would remain stored for the decades of the product's useful life. If subsequently those products were recycled, their carbon would remain stored even longer (Figure 9).

The carbon stored annually in harvested wood products in the U.S. is estimated to be the equivalent of 16 percent of the total annual carbon sequestration associated with forests (Domke et al. 2021). If forest stands that are harvested to produce wood products are promptly reforested, the new trees immediately begin to sequester more carbon from the atmosphere while the carbon stored in the wood products remains in those products.

The ability of forest thinning to increase carbon stored in wood products is illustrated in Figure 10 which summarizes Gingrich's (1971) yield relationships for upland oak forests, site index 65. With or without intermediate thinning treatments, the biomass, carbon, and board foot volume of a stand increase over time. However, stands with periodic thinning have greater cumulative yield over the life of the stand, provided the thinned trees are used for wood products or used as a substitute for materials produced using fossil fuels.

Not only do houses store carbon for a long period of time, they also store large quantities of carbon. Construction and maintenance of a typical house can store the equivalent of 100 metric tons of carbon dioxide for a century (Farmer, 2022; Bowyer et al., 2012).

Considerations relevant to carbon sequestration in wood products include the following:

- Other factors being equal, greater efficiencies result from producing long-lived rather than short-lived products.
- Following harvest, the residual or regenerating forest stands should be left in a condition to rapidly regrow and replace the carbon removed from the forest and stored in wood products.
- Carbon emissions associated with equipment used for harvesting, processing, and transporting wood products should be considered in estimation of net carbon storage derived from utilization of wood products.
- Managing waste wood can reduce CO_2 emissions. As waste wood decomposes it releases its stored carbon back into the atmosphere. Therefore, the less of it the better. It is noteworthy that in Missouri 96 percent of the residues from primary wood processing mills are utilized by secondary processing facilities (Goff et al., 2021).
- Additional opportunities to store carbon in wood products depend in part on the availability of product markets. For example, economic conditions that favor new construction create additional opportunities

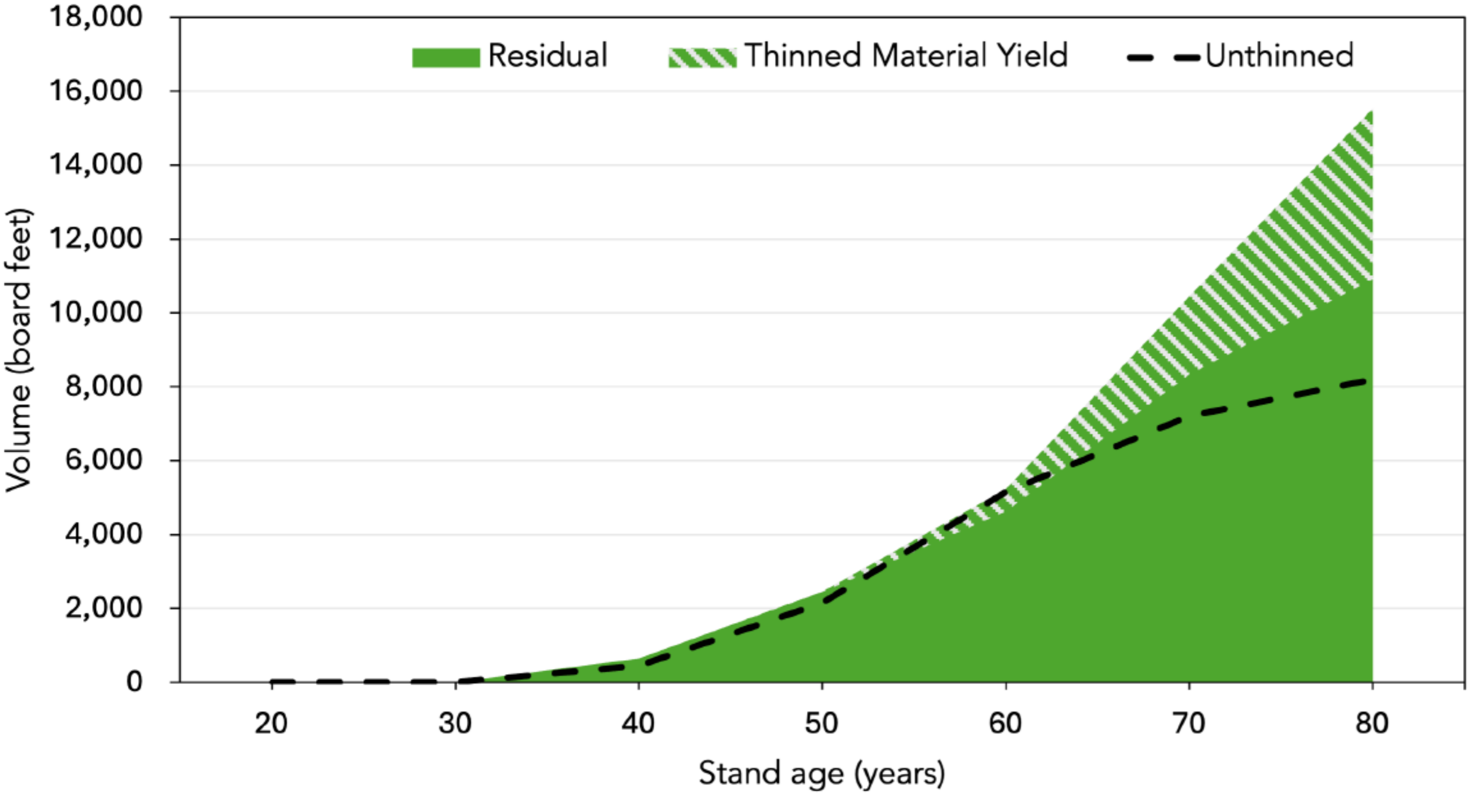

Figure 10. Comparison of cumulative board foot yield over time for thinned and unthinned oak forests in the Central Hardwood Region (Gingrich 1971, site index 65). For an unthinned stand (dashed black line), the board foot volume yield increases from age 30 through age 80, but the annual rate of increase gradually declines beginning around age 70. The total yield is greater for a stand that is thinned every 10 years beginning at age 30. The board foot volume of the live trees in the thinned stand (green area) is similar to that of the unthinned stand through age 60. After age 60, the yield of live trees in the thinned stand is greater due to a boost in tree growth as a response to the available growing space that resulted from the periodic thinning. In addition to the volume of live trees in the thinned stand, by age 80 the yield of thinned material has increased to approximately 4,000 board feet (green/white area). The cumulative yield for the thinned stand is nearly twice that of the unthinned stand. If the harvested volume generated by the thinnings is used for durable wood products, the total stored carbon in the thinned stand will exceed that of the unthinned stand.

End Use	Half-life of sequestered carbon (years)
Single-family homes (pre-1980)	80
Single-family homes (post-1980)	100
Multi-family homes	70
Nonresidential construction	67
Furniture	30
Railroad ties	30
Mobile homes	20
Manufacturing	12
Pallets	6
Free-sheet paper (chemical pulping; better quality)	6
Other paper	1

Table 1. Estimated longevity of carbon sequestered as forest products. The half-life is the estimated number of years until half of the carbon initially stored in the indicated wood product is no longer sequestered there. From Skog and Nicholson (2000).

Forest products have lower embodied energy than comparable products. The manufacture of forest products is also far less reliant on fossil fuels than other products. As a result, there is a beneficial substitution effect when wood is used in place of other types of building materials.

The energy required to produce wood products is lower than any other construction material.

Jim Bowyer, Dovetail Partners

store carbon in wood products. New technologies such as cross-laminated timber panels can expand opportunities for long-term carbon storage in wood products.

- In addition to the direct benefit of storing carbon in wood products, the wood products industry provides opportunities for employment, investment, and sustaining forest-associated communities.

8. Substitution of wood products and biomass for high-carbon alternatives

The previous section discussed how harvested wood products can increase the quantity of stored, forest-associated carbon. However, even greater carbon management benefits accrue when wood products are specifically targeted as substitutes for products that are energy-intensive to produce and that emit large quantities of carbon dioxide during manufacturing or use.

The greenhouse gas emissions associated with extraction, production, transportation and manufacturing a product are referred to as the product's embodied carbon. It is a measure of the relative environmental cost of creating and using alternative products (EPA, 2024b).

Wood products have low embodied carbon relative to other building materials such as cement, steel, plastic, glass and insulation (Bowyer 2012). Substituting wood products for materials that have greater embodied carbon means that in addition to the benefit of the carbon stored in the wood products, the fossil fuels that would have been needed to manufacture the replaced products are no longer required. This further reduces net atmospheric carbon emissions.

The use of cement in construction is particularly challenging with respect to CO_2 emissions, and substituting wood for cement in construction can be highly beneficial from a carbon management standpoint. Cement is used universally for construction. Manufacturing cement requires limestone to be heated to as much as 1400°F. This is typically done using fossil fuels that when burned release large quantities of CO_2 into the atmosphere. Moreover, the chemical reactions caused by heating limestone result in the emission of additional large quantities of CO_2 from the limestone into the atmosphere. It is estimated that 8 percent of global CO_2 emissions are the result of cement production. When possible, substituting wood for alternative products such as cement should have significant benefits in reducing CO_2 emissions (Fischetti et al. 2023).

Using wood biomass to produce energy (e.g., combustion in a steam boiler to produce electricity) is a special case of substituting wood to replace the fossil fuels (coal or natural gas) that would have otherwise been extracted from the Earth and burned for energy. Options for using biomass for energy production range in scale from residential wood stoves to powerplants that combust more than 250,000 tons of biomass annually-- enough to power 20,000 homes (Ever-green Energy 2024).

Notably, the University of Missouri utilizes a wood-fired boiler that is the centerpiece of its campus-wide renewable energy program. The University's combined cooling, heat, and power system runs in part (36 percent) on waste wood from Missouri sawmills and wood product manufacturers.

Accounting for the carbon sequestration, carbon emissions, and biomass harvesting associated with using wood for large-scale energy production is complex and case specific. Sustainable sourcing of biofuels is always a primary requirement.

One important consideration with respect to substituting wood biomass for fossil fuels in energy production is the origin of those fuels and their associated carbon. After being stored in the Earth for millions of years, fossil fuels (and their associated fossil carbon) are extracted and burned for energy. In the process fossil fuels release their formerly buried fossil carbon into the atmosphere as CO_2. Humans get the benefit of the energy produced, but there is no pathway to place the fossil carbon from fossil fuels back into the Earth where it came from. It remains in the atmosphere for centuries. In contrast, combustion using wood biomass for energy utilizes above-ground biofuels that are the product of photosynthesis. When wood biomass is burned as fuel, it also produces energy and releases CO_2 into the atmosphere. However, the expectation is that when trees used for biofuel are regenerated, the subsequent photosynthesis will cause those trees to grow and over time to sequester and store an amount of carbon comparable to that which was harvested and used as biofuel. There is a direct pathway for the carbon released from burning woody biomass to be sequestered and stored in the next generation of trees. The global benefit is that substituting biomass for fossil fuels results in less demand for fossil fuels, and therefore more fossil fuel and more fossil carbon remains sequestered underground than would happen otherwise. The limitation is that demand for energy far exceeds the capacity for biofuels to provide it.

9. Who decides?

There are many management strategies that can be employed to increase the quantity of carbon

Carbon is not the only critical ecosystem service that forests provide. Forests also cycle oxygen that we breathe and the water that we drink; they moderate temperature fluctuations, control soil erosion, and reduce flooding; and forests provide a local source of building materials and fuelwood, habitat for wildlife, and a place for recreation and cultural importance.

Alexandra Kosiba,
University of Vermont

stored in trees, in stands, on forest landscapes, and in forest products. Likewise, there are management strategies that can be employed to reduce carbon emissions associated with forest product manufacturing, construction, and energy production. The number of alternative carbon management scenarios is large, and their complexity is compounded by temporal considerations that affect the rate and timing of carbon sequestration and emissions (see Section 4). However, even simple management practices can help reduce carbon emissions and increase carbon storage.

Carbon management in Missouri forests must be an ongoing process. Suitable carbon management practices are likely to change over time in response to changes in forest conditions, changes in atmospheric carbon, changes in climate, and changes in sequestered carbon, along with consideration of forest management priorities associated with stewardship of wood, water, wildlife, recreation, forage and other ecosystem services that forests provide.

U.S. forests annually sequester the carbon equivalent of 14 percent of U.S. annual carbon dioxide emissions (11 percent of all greenhouse emissions) (Domke et al., 2021). That's a heavy lift. Globally, forests sequester more carbon than other terrestrial ecosystems (U.S. Global Change Research Program 2024).

Previous sections of this report discuss management practices that can increase the rate of carbon sequestration in forests. Implementation of those management practices can measurably increase the quantity of carbon stored in forest ecosystems, but it doesn't alter the fact that the driving force behind increased atmospheric carbon dioxide and associated climate change is the combustion of fossil fuels with their associated greenhouse gas emissions. Without massive reductions in greenhouse gas emissions, it is impossible to envision a future scenario where forest carbon sequestration and storage could offset a majority of annual greenhouse gas emissions.

In Missouri, 2.8 million acres of forest land (18 percent) are in public ownership. The majority of that acreage is national forest land (1.5 million acres) and state forest land (0.8 million acres), which is covered by formal forest management plans. Usually, those forest plans are formulated with public input and address multiple objectives. National concerns about climate change and associated carbon emissions are so widespread it seems inevitable that forest carbon management will become a significant consideration in forest management decisions for public forest land in Missouri and elsewhere.

In Missouri, 12.6 million acres of forest land (82 percent) are in private ownership. For Missouri's private forest land there are 359,000

Missouri private forest owners that decide if and how Missouri forests will be managed for carbon storage or for any other forest associated commodities, amenities, or ecosystem services. Among these private forest ownerships, about 70 percent are at least 50 acres in size (Oswalt 2019), large enough to warrant a formal or informal forest plan, if the owner chooses to develop one. It is notable that as a national group, U.S. family forest owners do not include producing forest products or storing carbon among their top three reasons for owning forest land. Instead, they cite beauty, wildlife, and legacy as their primary reasons for forest ownership (Butler 2020). Thus, it does not appear that carbon management per se will soon become a primary motivation guiding management decisions on Missouri's privately owned forest land.

Nevertheless, with or without a management plan, trees are going to grow larger and via photosynthesis they will accumulate more carbon. In fact, sequestering carbon is the "default setting" for forests. They are genetically programmed to accumulate woody biomass, half of which is comprised of carbon pulled from the atmosphere via photosynthesis. In much of Missouri, it takes more effort to stop forest growth and the associated carbon sequestration than it does to simply step back and let forests accumulate wood and store carbon. With or without forest planning, many forests in Missouri are going to continue to accumulate carbon—at least for a while.

This is not meant to imply that passive forest management—just leaving forests alone—is preferable to other management strategies for sequestering carbon. We saw in previous sections that active timber management can be highly compatible with sustained carbon sequestration and storage as well as production of marketable products. We also saw that producing wood products effectively stores the carbon contained in those products for their useful life, often many decades. Substitution of wood products (with low embodied carbon) for alternative materials such as steel, cement, glass, insulation, and masonry (with high embodied carbon) reduces the quantity of fossil fuels that would otherwise be extracted from the Earth during construction projects. We saw that using woody biomass to produce energy can reduce the demand for fossil fuels extracted from the earth and reduce the amount of fossil carbon released into the atmosphere. We know that for centuries forest products have sustained rural Missouri communities, and they continue to do so today. We know that forest management can help increase the rate of carbon accumulation in forest ecosystems and reduce carbon losses from natural and human-caused disturbances. We know the impacts of atmospheric carbon dioxide and associated greenhouse gases will continue to increase—probably for decades. And we know that forests play a major role in mitigating climate change.

So, who decides the future role of forests in climate change? Forest owners, forest managers, woods-workers, forest product manufacturers, and forest product consumers play the key roles, but we all have a part in shaping the future of Missouri forests.

The following section outlines management practices that can contribute to reductions in greenhouse gas emissions and help to moderate the future impacts of climate change.

There is no one answer when it comes to how to manage forests to maximize carbon sequestration. There are a lot of answers, and they all have to be put into the local context - the ecosystem, as well as the social and political context.

Rich Birdsey,
Woodwell Climate Research Center

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10. Practices that can increase forest carbon sequestration and offset carbon dioxide emissions

It is hard to conceive of future forest management scenarios where maximizing carbon sequestration is the sole management objective. In the future, however, carbon management may well become one of many considerations in most forest management decisions.

As we think holistically about forest resource management, forest sustainability, forest biodiversity, forest health, forest amenities, forest wildlife populations, and human socioeconomic values, it becomes apparent that a dynamic mix of forest conditions and age classes will be required to meet the multiple-use objectives that are invariably associated with forest management. There is no simple management approach that maximizes carbon sequestration in forests simultaneously over large landscapes for decades and longer, let alone one that addresses all the other considerations listed above. Nevertheless, there are numerous forest management practices that can increase the capacity of forests to sequester and store carbon with the intent of reducing the undesired impacts of climate change.

These forest management practices can increase carbon sequestration and storage.

1. Keep forests as forests. Forests accumulate and sequester carbon as they grow, and they do it faster and more efficiently than other terrestrial ecosystems. In contrast, converting forests to non-forest land uses has substantial impact on carbon--first by removing the carbon already stored and then by halting the future carbon accumulation that would have occurred if the land had remained forested.
2. Use afforestation to increase the area of forest cover. Forest ecosystems store more carbon per hectare than other land cover types.
3. In management decisions related to afforestation or forest regeneration, be mindful that over time climate change may alter the relative suitability of tree species for a given site. Make informed choices when selecting a stand's future species composition.
4. Quickly regenerate forests that are disturbed by harvest, insects, disease, wildfire, or severe weather. That allows forest sites to rapidly return to the process of carbon sequestration. Tree species such as oaks and hickories that readily resprout from the stump can be exceptionally efficient at reoccupying disturbed sites.
5. Minimize losses of soil and litter from forest ecosystems. Many disturbances to forest soil are human caused and avoidable. Soil and litter store large quantities of carbon per hectare (typically more per hectare than is stored in the corresponding forest biomass).
6. Maintain urban and suburban trees and forest communities—even small ones. They sequester carbon the same as rural trees and forests.
7. Keep forests healthy; trees that die and are unutilized for other purposes will decay and release their stored carbon into the atmosphere as the greenhouse gas CO_2.
8. Anticipate and manage forests to avoid disturbances that kill trees. The timing of disturbances is important. Missouri trees and stands can accumulate forest carbon over a period of ten decades or longer. Disturbances that kill trees, such as insects, diseases, severe weather, and wildfire can quickly convert a stand's living biomass to dead biomass that releases carbon dioxide. Replacing the lost biomass with an equivalent amount of live biomass may take another ten decades.
9. Keep forest stands fully stocked so the available growing space is fully utilized and the opportunities to sequester carbon via photosynthesis are maximized.
10. Consider managing stands for mixed species. Different species occupy different habitat niches, so species mixtures can be especially effective at occupying all the growing space in a forest stand and maximizing carbon sequestration in a stand.
11. Manage to create "resilient carbon" (Kosiba, 2023). Species diversity in stands and structural diversity across landscapes (i.e., diversity in tree sizes and stand ages) creates capacity

for resilience. Resilience allows stands and landscapes to readily recover from and adapt to unwanted forest disturbances that emit carbon dioxide into the atmosphere.

12. When possible, manage stands to increase carbon storage. It has been shown that some common silvicultural practices such as thinning can simultaneously increase carbon sequestration and output of harvested wood products.
13. Produce wood products. When harvested trees are turned into wood products, the carbon in those products remains stored there for the product's useful life, ranging from a few years or more than a century, depending on the product. The growing space released when trees are harvested for wood products allows the remaining trees or newly regenerated trees to sequester additional carbon from the same site. Over time, repeated harvests for durable wood products can compound the quantity of sequestered carbon originating from a site.
14. Substitute wood products for alternative materials that require more energy to manufacture. Wood products (low embodied carbon) that replace materials such as cement, steel, plastic, and insulation (high embodied carbon), reduce the use of fossil fuels and provide options for forest management.
15. Use wood as a biofuel in situations where it creates a positive carbon balance. Opportunities to use wood biofuels range from residential wood stoves to large-scale electric utilities with combined cooling, heating and electric power generation.
16. At the landscape scale, remain mindful of the patterns of forest carbon sequestration as forest stands age. Old forest stands (e.g., 80+ years) typically have accumulated more total biomass and carbon than younger stands. However younger stands (e.g., up to 60 years) typically have a faster annual rate of carbon sequestration than older stands. Landscape-scale forest planning can provide insights for a beneficial mix of age classes to support current and future carbon sequestration in forest stands.
17. Consider climate change to be a complicating rather than a dominating factor in silvicultural decisions (Johnson et al., 2019). It is now one more thing to consider when planning silvicultural treatments.
18. Manage proactively to anticipate future climate change. It is not a matter of if the climate will continue to change, but how much it will change. There is a growing body of knowledge about how tree species suitability across the landscape will change over time in response to climate change.
19. Whatever the forest management goals, follow best management practices applicable to the area. The Missouri Forest Management Guidelines (Missouri Department of Conservation, 2014), and Missouri Watershed Protection Practices (Missouri Department of Conservation, 2020) describe and illustrate land management practices and silvicultural practices that lead to sustainable forests, sustainable forest products, and sustainable ecosystem services. The guidelines are suitable for managing forest carbon as one of many forest products and ecosystem services.

Where do we begin with managing carbon? Review the list of management practices above. Add to the list based on your own experience. Identify practices you already follow. Select a few others to work on.

Start thinking about trees and forest products in units of carbon as well as in traditional units of board feet, cubic feet, basal area, and tons.

Work on ways to reduce fossil carbon emissions while continuing to work on ways for forest ecosystems to mitigate problems associated with the carbon dioxide already residing in the atmosphere. Many of us are fortunate to have the opportunity to work with forest ecosystems. Forest ecosystems have evolved over millennia to sequester and store carbon, and they do it better than any other terrestrial ecosystem. Missouri forests are going to continue to sequester and store carbon while simultaneously providing for our wellbeing in many other ways. It's what they are genetically programmed to do. We have options to either help or hinder that process.

GLOSSARY

Throughout this report the following terms are used in descriptions of carbon and biomass dynamics. The terms are defined here in the context of forest ecosystems and forest products.

Afforestation: establishing a forest in an area where the prior vegetation or land use was not forest.

Biomass: the weight (mass) of the organic matter in a tree, stand, or forest. Biomass is often summarized by components such as living or dead material; tree branches, boles, or roots; dry weight or green weight. Also see Carbon mass.

Biome: a biological community of interrelated plants and animals that has formed in response to its physical environment. Missouri is in the temperate forest biome.

Carbon dioxide: a molecule consisting of one carbon atom and two oxygen atoms. Carbon dioxide is the most abundant greenhouse gas in the atmosphere, and combustion of fossil fuels is the activity responsible for the majority of increases of greenhouse gases in the atmosphere.

Carbon dioxide emissions: when trees are burned or when trees or parts of trees decompose, they emit their stored carbon back into the atmosphere as carbon dioxide gas. Also, healthy, living trees respire as they grow, and like other organisms, trees release CO_2 as they respire. Carbon dioxide is also emitted when fossil fuels are burned. Currently, carbon dioxide emissions from combustion of fossil fuels greatly exceed the global capacity of forests to sequester and store that quantity of carbon. Consequently, the concentration of CO_2 in the atmosphere has been gradually increasing for decades.

Carbon mass: carbon mass is the weight of carbon in a tree, stand, or forest. For common Missouri tree species, the amount of carbon they contain is equivalent to about half of the tree biomass dry weight.

Carbon sequestration: the process in which trees capture carbon dioxide gas from the atmosphere and via photosynthesis create carbohydrate molecules consisting of carbon, oxygen, and hydrogen. Trees use carbohydrate molecules to form wood, bark, and other tree structures. In the process of photosynthesis, carbon that was previously in the atmosphere as CO_2 is converted to carbon stored within a tree, and spare oxygen molecules (O_2) are released into the atmosphere.

Carbon sink: a tree, stand, or forest that is a net accumulator of carbon dioxide is a carbon sink. Also see carbon source.

Carbon source: a tree, stand, or forest that is a net emitter of carbon dioxide into the atmosphere is a carbon source. Trees that die become carbon emitters when they decompose and release carbon dioxide into the atmosphere. Trees that burn become carbon emitters. Fossil fuels that are burned become a carbon source as they emit carbon dioxide into the atmosphere. Also see carbon sink.

Dry weight: the weight of biomass that has been dried to a zero percent moisture content. In most situations, biomass equations are used to estimate a tree's biomass dry weight as a function of the tree's diameter (dbh). Biomass is usually reported as dry weight. Also see green weight.

Ecosystem services: the benefits that people receive from ecosystems. Ecosystem services from forests include wood, water, recreation, food, cultural and spiritual values, wildlife habitat, nutrient cycling, carbon cycling, and more.

Embodied energy: the sum of energy (or of emitted carbon) required to produce a product. Using materials with low embodied energy (like wood) in place of materials with high embodied energy (like steel and cement) reduces net carbon dioxide emissions.

Fossil fuels: nonrenewable fuels that are derived from ancient accumulations in the Earth's crust of compressed plant and animal matter. Examples include coal, natural gas, and petroleum products. Fossil fuels include hydrogen and carbon; when they are burned, they release carbon dioxide into the atmosphere.

Green weight: the weight of wood, logs, or biomass measured without regard to the moisture content. The green weight of a freshly cut tree could be twice the dry weight of the same tree, so it is important to distinguish dry vs. green weights when estimating biomass and carbon. Also see dry weight.

Greenhouse effect: the greenhouse effect refers to the ability of greenhouse gases to trap heat in the atmosphere in a manner similar to the way a greenhouse traps heat. Also see greenhouse gas.

Greenhouse gas: a gas that traps heat in the atmosphere. Examples include carbon dioxide, methane, and water vapor. The greater the concentration of greenhouse gases in the atmosphere, the more heat that is trapped. Also see greenhouse effect.

Harvested wood products (HWP): wood products derived from trees. Just as living trees store carbon in wood, wood products made from trees also store carbon. Wood products protected from decay and burning can store carbon for periods of a few years to a century, depending on the useful life of the particular wood product.

Net zero (or carbon net zero): the condition where the quantity of greenhouse gases emitted to the atmosphere by use of fossil fuels is offset by an equivalent quantity of greenhouse gases removed from the atmosphere by photosynthesis and carbon storage, or by other means.

Photosynthesis: the process by which green plants absorb carbon dioxide and water; in the presence of sunlight create carbohydrate molecules; and release oxygen into the atmosphere.

Sequestered carbon: stored carbon that has been sequestered via photosynthesis.

Stored carbon (or carbon storage): the quantity of carbon that is stored in a tree, stand, or landscape, and/or the quantity of carbon stored in wood products such as flooring, cabinets, pallets, and cooperage. Typically, the carbon stored in a tree remains there until the tree (or parts of the tree) die and begin to decompose, or the tree is burned. Trees that decompose or are burned emit their carbon to the atmosphere as CO_2 gas. Also see carbon sink and carbon source.

Substitution: when wood (which has low embodied energy) is used as a substitute for products that have a high embodied energy, it reduces the net carbon emissions that otherwise would have taken place. Similarly, biofuels can be substituted for fossil fuels in energy production, reducing emissions of fossil carbon associated with burning fossil fuels.

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