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Considering Forest and Grassland Carbon in Land Management

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Considering Forest and Grassland Carbon in Land Management

ABSTRACT

Forest and grassland ecosystems in the United States play a critical role in the global carbon cycle, and land management activities influence their ability to absorb and sequester carbon. These ecosystems provide a critical regulating function, offsetting about 12 to 19 percent of the Nation's annual greenhouse gas emissions. Forests and grasslands are managed for many different objectives and a variety of goods and services, including clean water, clean air, biodiversity, wood products, wildlife habitat, food, recreation, and carbon sequestration. Although carbon may be of interest in developing management plans and options, it may not be a primary management objective. The amount of carbon absorbed by, and stored within, a particular ecosystem can be affected by many factors related to land management, including land-use change, management activities, disturbance, the use of harvested wood, and climate. The long-term capacity of forest ecosystems to absorb and sequester carbon depends in large part on their health, productivity, resilience, and ability to adapt to changing conditions. This report describes the role of forest and grassland ecosystems in the carbon cycle and provides information for considering carbon as one of many objectives for land management activities.

KEY WORDS

afforestation; avoided deforestation; carbon storage and sequestration; greenhouse gas mitigation; wood biomass energy; wood products

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Introduction: Considering Carbon in Land Management

Human activities such as fossil fuel use, industrial activities, land-use change, livestock management, and agriculture lead to greenhouse gas emissions, including carbon dioxide, methane, and nitrous oxide. Greenhouse gas emissions contribute to climate change, altering temperature and precipitation patterns. Global atmospheric concentrations of greenhouse gas have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values (U.S. CCSP 2007, IPCC 2014a).

Forests in the United States are an important carbon sink. Carbon dioxide uptake by forests in the contiguous United States offsets about 12 to 19 percent of our total carbon dioxide emissions each year (Ryan et al. 2010). Carbon sequestration is only one of many services provided by forests and grasslands; others include clean water, clean air, biodiversity, wood products, wildlife habitat, food, and recreation. Considering carbon in land management activities must be done in the context of the agency's multiple-use mission.

The long-term capacity of forest ecosystems to capture and store carbon depends in large part on their health, productivity, resilience, and adaptive capacity. Ecosystems are dynamic and are affected by temporal and spatial variability in temperature and precipitation, insect and disease epidemics, wildfires, catastrophic storms, and human activity.

Land management in a dynamic system considers cumulative effects across time, factoring in risk, severity, scale, and likely outcome of disturbances. For example, storing carbon in overly dense forests increases the risk of losing the carbon through fire and decomposition of fire-killed trees following large wildfires (Hurteau and Brooks 2011). Dense stands are less vigorous and more susceptible to insect attack (Chadwick and Larson 1996). Land management programs that restore forests to healthy and productive conditions will help ensure the long-term maintenance and transformation of forest carbon stocks. Ecosystems managed to adapt to changing conditions will capture carbon and store it more securely over the long term, while also furnishing wood-based materials.

Traditionally forest management has focused on optimizing a given good or service (e.g., volume harvested per surface unit). As needs and demands evolve, management is changing to focus on providing a suite of goods and services. Optimizing—not maximizing—carbon sequestration in forest ecosystems and effectively substituting forest-based materials for fossil fuel-intensive materials in the context of providing other needed goods and services can be a sustainable, long-term means of responding to climate change. Sustainable carbon management involves effectively managing

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ecosystems by restoring, maintaining, and enhancing their health and productivity; and applying management practices that increase sequestration or offset emissions, as well as taking account of the carbon in wood products and substitutions that result from managed forests in the long term.

Forest management activities play a critical role in ensuring that ecosystems remain a net carbon sink. The U.S. Department of Agriculture, Forest Service's management response focuses on a three-fold approach: adaptation, mitigation, and sustainable consumption. The agency is responding to changing weather patterns through adaptive restoration—by restoring, creating, or maintaining functions and processes characteristic of healthy ecosystems in the context of changing climate and dynamic demands on the resource. The Forest Service is restoring and managing ecosystems across landscapes, working with State and private partners, and developing science and tools to provide key functions and increase ecosystem resilience to stresses and uncertainties associated with changing weather patterns.

In the broad sense, as natural resource professionals in the Forest Service, our desired resource outcome is that forest systems are healthy, productive, and resilient, and provide a sustainable supply of goods and services that enhance the quality of life for present and future generations. To meet this goal, we must consider and manage for the range and quantity of goods and services that we will require our lands to provide in the coming decades. In significant measure, we will expect these lands to produce water, wood and nonwood products, recreational opportunities, varying habitats, climate change mitigation, and energy needed by our growing population and its economies. The key is acting in the present to deliver in a changing future. This publication summarizes information and science helpful when considering carbon in land management activities.

Chapter 1: Global Carbon Cycle

Natural resource professionals and landowners have long managed forests for numerous values, including clean air and water, wood products, fisheries and aquatic habitat, wildlife, recreation, aesthetics, traditional and cultural uses, and nontimber forest products. A more recent addition to these multiple forest uses is the sequestration of atmospheric carbon for greenhouse gas mitigation and the stewardship of carbon in biomass and soils. This forest use, "carbon stewardship," has risen in prominence as the understanding of the causes, effects, and pace of global climate change has progressed. The increasing focus on carbon stewardship provides an opportunity to think about land management in new ways and engage with new stakeholders, but it also compels land managers to spend some time learning about global, regional, and stand-level carbon cycles and issues. This chapter outlines the global carbon cycle and the contribution of forests and other ecosystems to provide context for subsequent chapters describing forest carbon dynamics and the consideration of carbon in land management.

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CARBON AROUND THE WORLD

Carbon is one of the most important elements found on Earth. The carbon cycle supports all life by transferring carbon between living things and the environment. Across the globe, carbon is stored in different places and in different forms. The amount of carbon stored in a particular system is called a "stock" or a "pool" (fig. 1). The atmosphere is one carbon stock, for example, and contains 839 gigatons of carbon (Gt C), mainly in the form of carbon dioxide (CO_2). The Earth's largest carbon stock is found within the continental crusts and upper mantle of the Earth (122,576,000 Gt C), a large portion of which is sedimentary rock formed over millions of years (Mackenzie and Lerman 2006). Oceanic carbon is the next largest stock (37,100 Gt C). More than 95 percent of oceanic carbon is mainly present in the form of inorganic dissolved carbon, while only 900 Gt C is available for exchange in the surface ocean. Soils store approximately 1,325 Gt C in the top 1 meter of soil alone and 3,000 Gt C in total when soil at deeper depths is included, although large uncertainties are introduced due to unconstrained soil properties (such as peat bulk density and estimates of permafrost at depth, among others)(Köchy et al. 2015). In addition, permafrost (frozen soil) stores a large pool of carbon that is climatically protected from decomposition (Trumbore 2009; Schmidt et al. 2011), although more and more of this pool is becoming available as the average global temperature rises (Schuur et al. 2015, Guido et al. 2016).

Plants take up carbon through photosynthesis, and this carbon is subsequently allocated above- and belowground, contributing to the global vegetation stock. Globally, forests account for 92 percent of all terrestrial biomass, storing approximately 400 Gt C (Pan et al. 2013), but this is not homogeneously distributed across the Earth. Different forest ecosystem types store different amounts of carbon, and much of this variation is related to the climate found in a particular part of the world (fig. 2). Tropical forests account for two-thirds of all terrestrial biomass (262 Gt C), while temperate (47 Gt C) and boreal (54 Gt C) forests each contain about 20 percent of the amount of carbon found in tropical forests (Pan et al. 2013). The carbon stored aboveground in leaves, branches, and stems relative to the amount stored belowground in soil aggregates and plant roots depends on regional climate. Patterns in carbon distribution can easily be viewed at a global scale. The wet-warm region of the Tropics has much more carbon stored aboveground compared to belowground. In contrast, the cool regions of the boreal forest have enormous belowground carbon stores. The temperate zone (cool, dry and moist ecosystems) is more complex, as both temperature and water availability constrain carbon input through photosynthesis and output through decomposition. An objective of carbon stewardship is to manage the land so that carbon remains in the forest rather than being released as greenhouse gases such as CO_2 or methane (CH_4).

BOX 1

Carbon Terms and Units

The carbon cycle can be thought of as consisting of two parts.

- **Carbon stocks (**or **pools)** refer to the amount of carbon that is stored in a particular place, such as the ocean or the atmosphere.

1 Gigaton (Gt) = 1 Billion metric tons = 1 Petagram (Pg) = 1×10^{15} g

1 Megaton (Mt) = 1 Million metric tons = 1 Teragram (Tg) = 1×10^{12} g

- **Carbon fluxes** refer to the transfer of carbon between different stocks. Carbon emissions (primarily in the form of carbon dioxide) from human combustion of fossil fuels is one example of a flux; in this process, carbon is transferred from geologic reservoirs to the atmosphere.

Gigatons per year = Petagrams per year

Megatons per year = Teragrams per year

- **Carbon density** is another way of referring to the amount of carbon within a certain area:

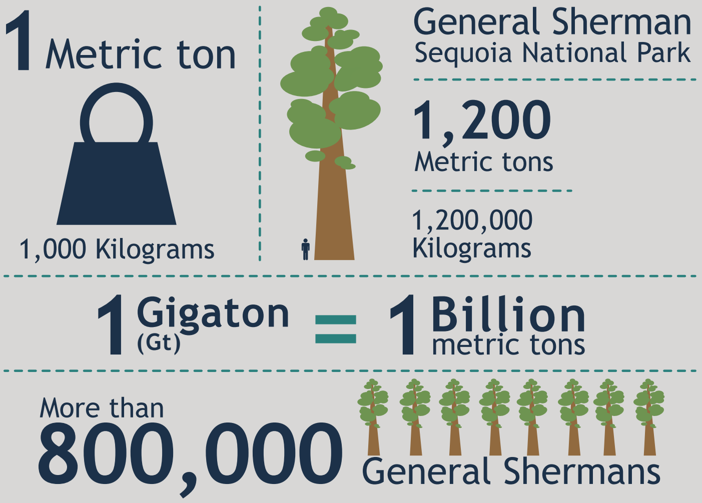
TONS per hectare

Kilograms per square meter = 10 TONS per hectare

- **Carbon turnover** refer to the amount of time carbon is cycling in a system in units of years. This is often referred to as mean residence time.

BOX 2

Gigaton Visualization



1 Metric ton

1,000 Kilograms

General Sherman
Sequoia National Park

1,200
Metric tons

1,200,000
Kilograms

1 Gigaton (Gt) = 1 Billion metric tons

More than
800,000 General Shermans

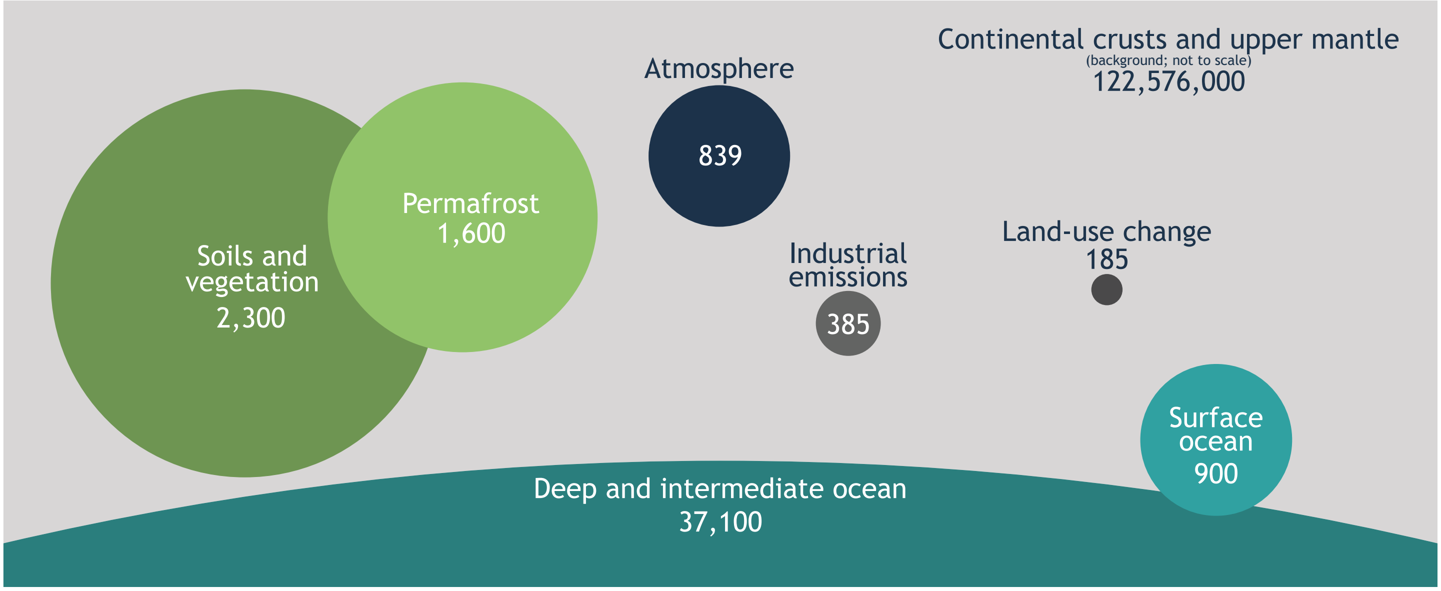


Figure 1. Global carbon stocks (carbon stored in pools), shown in gigatons.

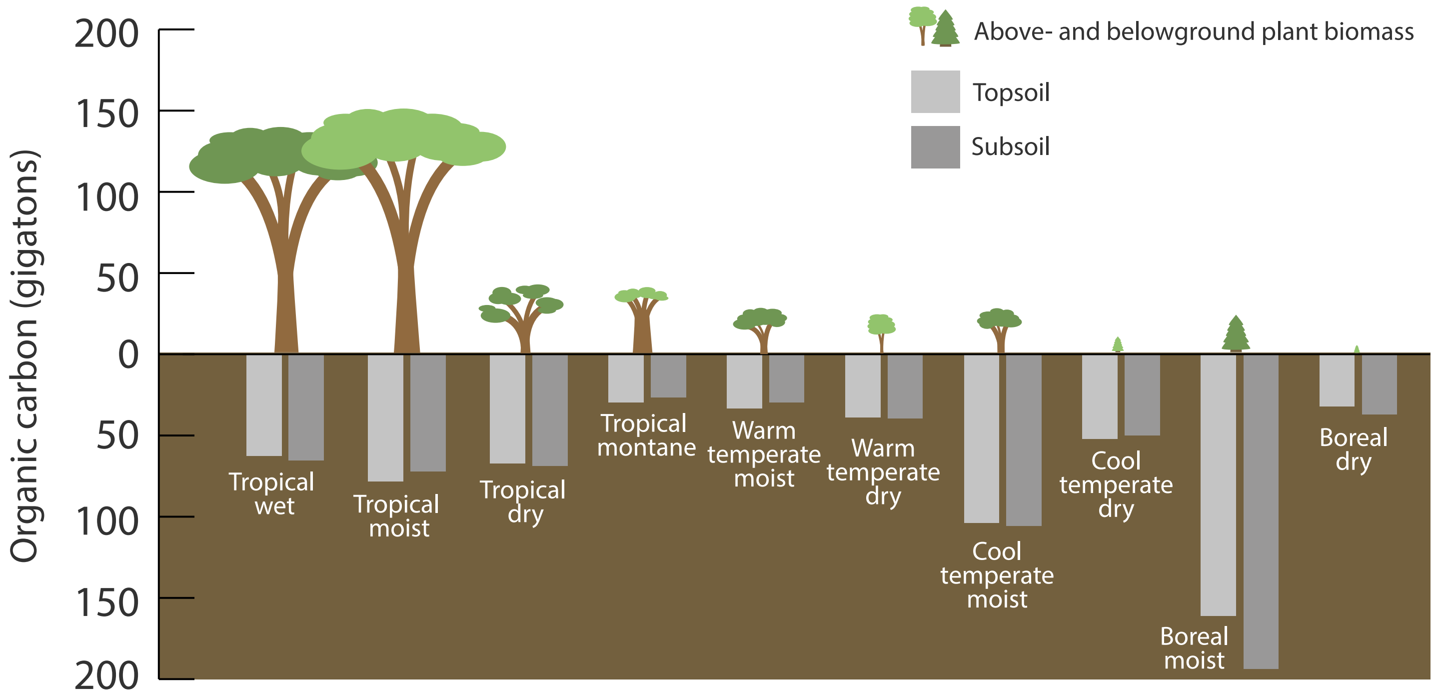


Figure 2. Carbon stored in ecosystems, shown in gigatons. Data from Scharlemann et al. (2014).

GLOBAL CARBON FLUXES

Carbon is exchanged between different stocks in the land, ocean, and atmosphere. This means that carbon in many stocks, whether global or local, is not necessarily static and in many cases can be quite dynamic. Carbon that enters or leaves a stock is referred to as a flux, and the average rate at which carbon flows through a stock is called carbon turnover. The duration of time that carbon stays in an ecosystem, or the turnover of the carbon within an ecosystem, depends largely on climate, soil, vegetation type, and their interactions. The turnover of carbon within ecosystems across the globe gives an idea of where carbon might be most vulnerable to release as CO_2 to the atmosphere (fig. 3). Thus, tropical forests may contain a lot of aboveground carbon, but it does not stay in the forest very long (14 years on average) due to high decomposition rates, which corresponds to a relatively low soil carbon storage (Carvalhais et al. 2014). Similarly, the biomes with extreme climates or those that are very dry have the longest turnover times (e.g., 66 years on average in tundra ecosystems) (Carvalhais et al. 2014), emphasizing the role of climate in maintaining sequestered carbon (Schmidt et al. 2011). Estimating carbon turnover with climate models is challenging, and large variations in projected future terrestrial carbon cycling highlight the need for more information regarding the effect of vegetation type, mortality, and recruitment on turnover (Friend et al. 2014). The availability of soil carbon to microbial breakdown or leaching is regulated by several factors related to climate, connectivity to microorganisms and enzymes, and associations with soil minerals and aggregates (Schmidt et al. 2011). Furthermore, disturbances such as fire or insect outbreak and even land-use change or forest harvest can lead to dramatic shifts in both aboveground and belowground carbon. Knowledge of turnover within ecosystems can inform management decisions that affect the rate of carbon turnover, ultimately influencing the flux of carbon into and out of ecosystems.

Fluxes are typically quite small compared to stocks, but even small shifts in the sizes of global fluxes have had a profound effect on the global carbon cycle and have strongly influenced the rate of climate change (Cramer et al. 2001, Luo 2007). Carbon moves from the atmosphere to land primarily through photosynthesis (fig. 4). Carbon also transfers from land back to the atmosphere through plant and soil respiration, litter decomposition, and the combustion of plant biomass in fires. In contrast, ocean contributions depend on complex physical processes of mixing, ocean chemistry, and biological uptake (Lauderdale et al. 2016). The oceans emit on the order of 78.4 Gt C per year and take up 80 Gt C per year, while land releases 119 Gt C per year and takes up 123 Gt C per year. Overall, both oceans and land take up more carbon than they release in a year, yielding a net uptake of 2.3 Gt C per year (ocean) and 2.6 Gt C per year (land). Emissions from human activity, including fossil fuel combustion and greenhouse gases released from land-use change, are 9 Gt C per year (Ciais et al. 2013).

The primary flux of CO_2 into forests occurs by photosynthesis, while respiration and decomposition are the primary fluxes out. The relative balance of these currently results in an overall uptake of carbon—a global carbon sink. The uptake of carbon through forest ecosystems varies widely by forest type, with tropical forests at the high end taking up nearly 22 Gt C per hectare per year, temperate forests 17 Gt C per hectare per year, and boreal forests 10 Gt C per hectare per year (Xu et al. 2014). These values are gross primary production values and are offset by respiration losses that are similar in rank, with tropical forests having the the highest net ecosystem production at 6.6 Gt C per hectare per year. Temperate forests have intermediate net ecosystem production of 4.4 Gt C per hectare per year, and boreal forests have the lowest at 2.8 Gt C per hectare per year (Xu et al. 2014). Mean annual temperature and moisture explains much of the variation in these flux rates; however, the net fluxes—that is, the net ecosystem production—are often mediated by nutrient availabilities or soil conditions such as flooding, which can have a negative effect on production. Stand development also plays a role in the net amount of CO_2 flux into forests. Stands at a young development stage have the lowest influx of carbon relative to the carbon respired, while middle-stage stands have the greatest net influx. Importantly, mature and old-stage stands also take in more carbon than they release, despite an increase in

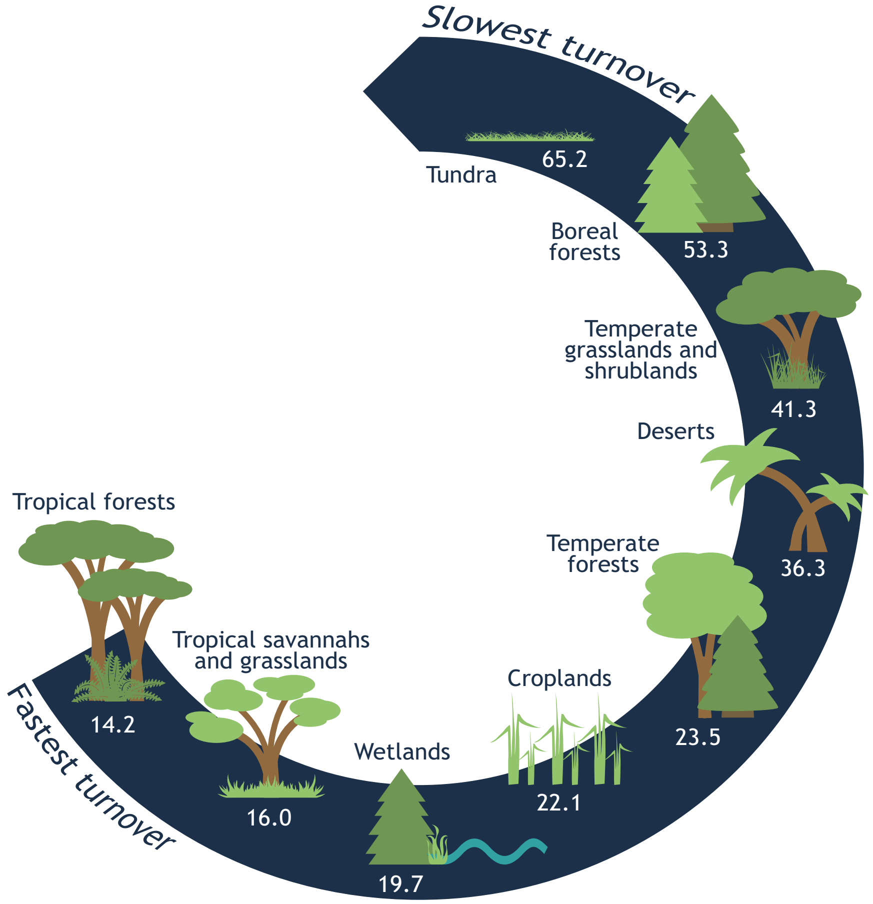


Figure 3. Average ecosystem turnover times (years) of different terrestrial carbon pools.

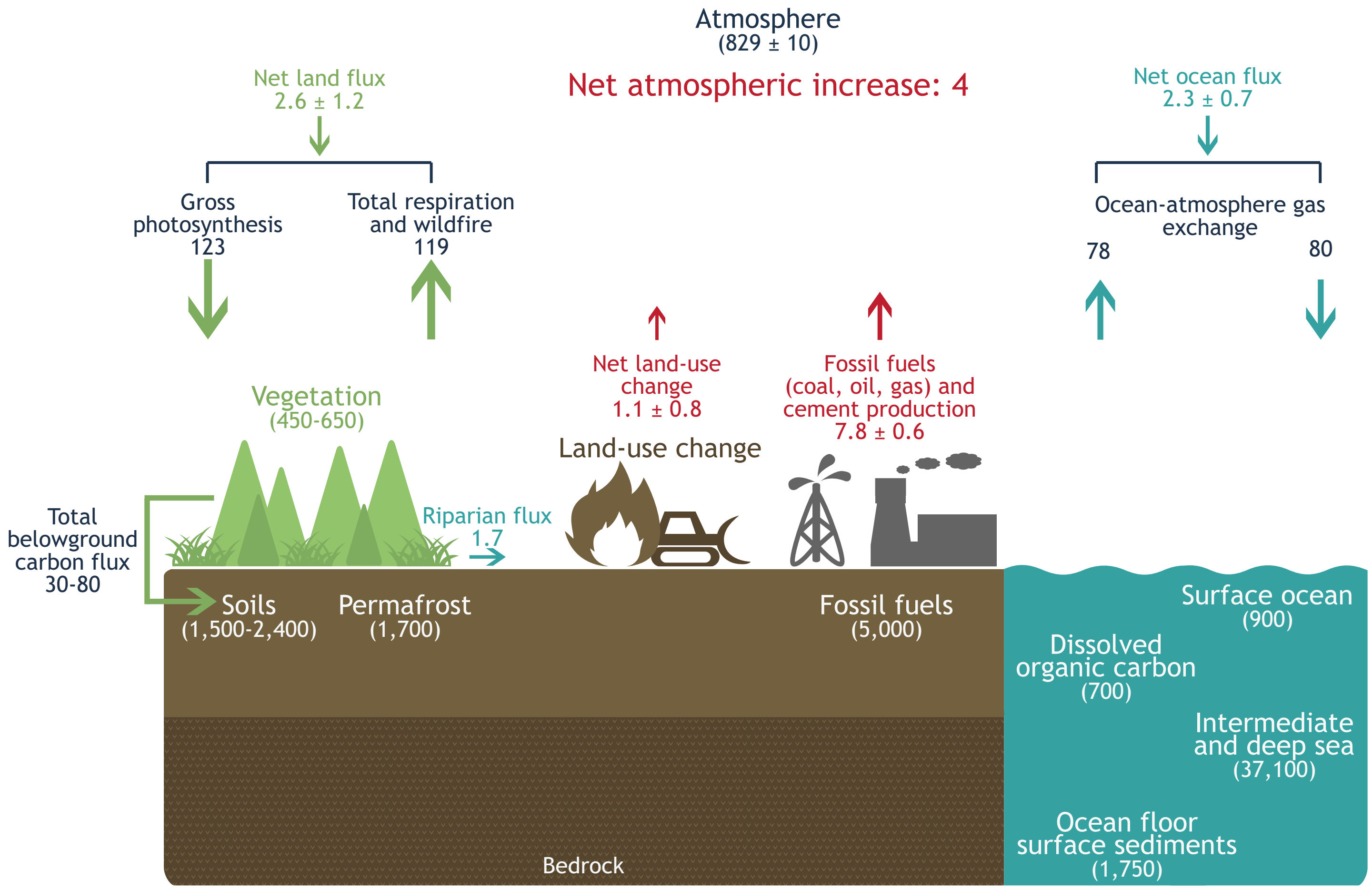


Figure 4. Global carbon cycle. Carbon (Gt C) stocks are denoted in parentheses and shown in gigatons. Fluxes (Gt C per year) are associated with arrows and shown in gigatons per year.

the respiratory flux out of the forest (Xu et al. 2014). Trees, in fact, show a tendency to accumulate more carbon with increasing size (Stephenson et al. 2014).

Carbon emissions to the atmosphere from human activity (predominantly the result of fossil fuel combustion and land-use change) have been rising since the industrial revolution. Fossil fuel combustion has contributed nearly 385 (+/- 20) Gt C since the industrial revolution, or about 70 percent of the total anthropogenic contribution since 1750 (570 +/- 70 Gt C) (Canadell and Schulze 2014). Land use and land-use change constitute the remaining 30 percent of emissions for the same time period, or 185 (+/- 65) Gt C. Patterns in land-use change have varied over the decades, leading to stronger CO_2 emissions or uptake. Emissions associated with current land use and land-use change are largely attributed to deforestation and forest degradation, mostly in the tropics, amounting to 2.8 (+/-0.5) Gt C per year (Le Quéré et al. 2015). Afforestation and forest regrowth have increased the terrestrial carbon sink; in fact, shifts in forest management are considered an important contribution to the growing CO_2 sink (Erb et al. 2013), along with the physiologically related forest CO_2 uptake that occurs with increased CO_2 concentrations.

Carbon and Climate Change

The amount of carbon stored in the Earth's atmosphere is miniscule compared to the amount stored in oceans, soils, and geologic formations (fig. 4). When looking across different carbon fluxes, both the amount and the direction of carbon that is moving among pools can have a big impact on climate change. Small additions to the atmosphere over a long time have an enormous effect on the global carbon cycle. The start of the industrial revolution nearly 300 years ago marked the beginning of the period during which human (anthropogenic) activities moved larger amounts of carbon from different terrestrial and geologic stocks to the atmosphere. Emissions from fossil fuel use and land-use change have been increasing over the last three centuries and currently result in a net addition of approximately 9 Gt C per year to the atmosphere (fig. 4). When combined over time, these anthropogenic fluxes have resulted in a 19- to 36-percent shift of carbon out of the Earth's gas, oil, and coal reservoirs (geologic stocks)—carbon that had been essentially locked away from the carbon cycle for millions of years but is now expected to remain in the atmosphere for decades to centuries. This cumulative flux of fossil fuel carbon to the atmosphere can be considered a *net addition* to the contemporary carbon cycle and a driver of climate change (IPCC 2014a).

Human-caused (anthropogenic) carbon emissions have affected not just the atmosphere but also the ocean and land stocks. In fact, the carbon storage of oceans and vegetation on land has increased over the past two centuries, slowing the net increase in atmospheric CO_2. Flux changes to the large ocean carbon stock have shifted the ocean from a net source of carbon to the atmosphere to a net sink from the atmosphere, such that 2.3 Gt C of carbon is taken up by the oceans annually. Likewise, when compared to the estimated rate of uptake in the 1750s, the rate of atmospheric CO_2 net uptake by terrestrial biomes has nearly doubled to over 2.6 Gt C per year. Vegetation, overall, has increased in the rate of uptake by approximately 14.1 Gt C per year, and this productivity has actually been enhanced by elevated atmospheric CO_2 through "CO_2 fertilization." The terrestrial carbon sink may continue to grow from the CO_2 fertilization effect, or it may stall due to a lack of nutrients or water available for plant growth. Neither the terrestrial nor ocean sinks are currently able to keep pace with anthropogenic emissions, however, so the atmospheric CO_2 stock will continue increasing unless slowed by other means.

The atmosphere has retained 250 Gt of added carbon since the 1750s. It is estimated with high confidence that hundreds of thousands of years are needed for the land and oceans to remove the total anthropogenic carbon that has been emitted thus far (Ciais et al. 2013). The approximately 5 Gt C currently removed from the atmosphere annually by ocean and land still results in a net accumulation of 4 Gt C per year in the atmosphere. Thus, this amount of carbon added over two centuries to an atmospheric carbon pool that was approximately 589 Gt C in 1750 has resulted in an atmosphere that now contains in excess of 800 Gt C—small additions over a long time matter. This increase in atmospheric CO_2 will continue to drive harmful climate feedbacks, such as rising ocean CO_2 storage, which increases ocean acidification and decreases oxygen levels (Levin and Le Bris 2015). Major climate feedbacks on land include permafrost thawing, freeing previously climatically protected carbon and releasing even more CO_2 and CH_4 into the atmosphere. Other feedbacks include a potential increase in plant respiration (release of CO_2 back into the atmosphere) or shifts in hydrology such that carbon stored in wetlands and peatlands are exposed to aerobic microbial decomposition (Regnier et al. 2013). Increased frequency and intensity of drought, flooding, hurricanes, and other climate extremes have the potential to exacerbate terrestrial climate-carbon feedbacks (Frank et al. 2015).

SUMMARY

Forests and other terrestrial ecosystems are a major component of the global carbon cycle and involve massive fluxes of CO_2 between vegetation, soils, and the atmosphere. Greenhouse gas fluxes from fossil fuels to the atmosphere are small in comparison to the amount of carbon exchanged between vegetation and the atmosphere. However, the increase in emissions resulting from fossil fuel combustion and land-use change represent a net addition of carbon to the atmospheric carbon stock, resulting in global warming and associated climate change. Even small changes in the fluxes between terrestrial ecosystems and the atmosphere can have a large effect on the accumulation of CO_2 in the atmosphere. Land management cannot completely offset fossil-derived greenhouse gas additions, but forests are a critical component of our national efforts to mitigate national and global emissions. The following chapters further address the stocks and fluxes of forest carbon at finer scales, as well as the capacity of forests to mitigate greenhouse gas emissions, including ways that carbon outcomes may be included in land management.

Chapter 2: Ecosystem Carbon Storage and Fluxes

INTRODUCTION

The carbon balance of the terrestrial biosphere is the focus of an international, multidecadal, and interdisciplinary research program seeking to understand: (1) the factors that drive carbon uptake, release, and storage; and (2) opportunities for management to enhance storage by increasing uptake while limiting release (Ryan et al. 2010, U.S. CCSP 2007). Because of the enormity of the flux terms associated with regional to global carbon fluxes (Bonan 2008, fig. 1), even small errors in estimated sensitivities to the drivers of uptake and release can scale to very large shifts in forecasted terrestrial carbon balance and underlying predictions of terrestrial carbon gain or loss (Grace and Rayment 2000, Ryan et al. 2010, McKinley et al. 2011). Globally, carbon is held in surface and deep ocean waters, in soils and permafrost, in terrestrial vegetation, and in the atmosphere (fig. 4). These carbon stocks are dynamic and exchange with each other, with some fluxes dwarfing the annual flux of fossil carbon to the atmosphere. Important to this chapter is the flux of carbon from the atmosphere into the terrestrial biosphere (123 gigatons of carbon [Gt C] per year), as well as the flux of carbon from the terrestrial biosphere back to the atmosphere through respiration and fire (119 Gt C per year), with the large majority of this flux approximately equally split between soil respiration and respiration from living aboveground biomass.

Over the past 50 years, terrestrial carbon cycling science has focused on the following main factors controlling carbon storage and underlying process rates that control terrestrial carbon balance: temperature (Ryan 1991, Giardina and Ryan 2000, Davidson and Janssens 2006, Ryan et al. 2010, McKinley et al. 2011), atmospheric chemistry (Norby et al. 2005, King et al. 2005), moisture (Burke et al. 1989, Epstein et al. 2002, Luyssaert et al. 2007), soil physical and chemical properties (Binkley and Fisher 2013), vegetation type (Vitousek 1990, Binkley and Fisher 2013, Peltzer et al. 2010), hydrology (Binkley and Fisher 2013), and disturbance history (Pregitzer and Euskirchen 2004). Temperature, moisture, and disturbance are of particular interest because they are dynamic over time and increasingly have become influenced by human activities (IPCC 2014a), especially current changes in the atmosphere that drive global climate. Through acceleration of carbon losses relative to uptake, such changes can also enhance other alterations of the global climate (Davidson and Janssens 2006). Disturbance is of particular interest because time-since-disturbance is a central driver of carbon storage in living biomass (Pregitzer and Euskirchen 2004, Ryan et al. 2010), and conversely, anthropogenic disturbance or human-caused changes to natural disturbance regimes can affect the extent, return interval, duration, and

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severity of disturbances, with impacts to landscape and to region carbon storage. Temperature, moisture, and disturbance exert their influence on carbon balance across landscapes that vary with respect to soils, vegetation, elevated carbon dioxide (CO_2), and hydrology. These factors can modify (positively or negatively) the effects of temperature, moisture, and disturbance. For example, soil fertility exerts a dominant influence on productivity, which in turn influences storage, and which can outweigh differences in temperature or moisture (Binkley and Fisher 2013). Other interactions are more subtle. For example, soil fertility and species type can influence the extent to which vegetation growth responds to elevated CO_2 (Norby et al. 2005).

To better understand factors that control terrestrial carbon balance, it is valuable to understand how gross primary production and ecosystem respiration (R_E) are regulated at the stand scale. Gross primary production is the sum of total canopy photosynthesis for a unit of area over a given unit of time (Baldocchi and Amthor 2001). Biochemically, this is the process of converting light into chemical energy, whereby CO_2 plus water (H_2O) leads to formation of oxygen (O_2) plus carbohydrates (CH_2O). Light levels, chlorophyll and photopigment content effects on enzyme activity, temperature effects on enzyme activity, and CO_2 and water effects on substrate supply all positively influence (within limits) rates of photosynthesis (Baldocchi and Amthor 2001). Similarly, but in the opposite direction, respiration represents the conversion of chemical energy into potential energy and heat whereby O_2 plus CH_2O combine to form CO_2 plus H_2O. Reaction rates are controlled by respiratory substrate supply (itself regulated by photosynthesis), enzyme content, and temperature via influence on enzyme activity (Amthor and Baldocchi 2001).

Ecosystem respiration (R_E) represents both autotrophic (R_A) and heterotrophic (R_H) sources of respired carbon. With the release of R_A, the fraction of gross primary production that remains in an ecosystems is most often called net primary production. Aboveground net primary production includes bole wood and branch growth, leaf production, and any production lost to herbivory (Clark et al. 2001). Belowground net primary production includes coarse and fine root growth, exudation of carbon into the rhizosphere, and root growth lost to herbivory (fig. 5). There are also gray areas—for example, carbohydrates are sent to mycorrhizae and respired during acquisition functions (Litton and Giardina 2008); these could be categorized as autotrophic respiration (because mycorrhizae perform the functions of roots, and are often viewed as extensions of the root system) or heterotrophic respiration (because it has left the plant and is performed by microbial organisms).

Following senescence of plant parts (e.g., foliage and branch death, tree mortality), the amount of live carbon left in an ecosystem is reduced. Over time, senesced plant materials decompose and are converted back to CO_2. The remaining carbon fixed in a given year being is called net ecosystem production and refers to the portion of gross primary production that is left after R_E (summing both R_H and R_A). Scaled over larger areas of land, net ecosystem production is often referred to net biome production.

Decomposers ultimately regulate storage of detrital carbon by controlling the rate at which detritus is converted to CO_2 versus microbial biomass and the precipitated byproducts of microbial decomposition and turnover. There are important questions, however, regarding sensitivity of the decomposition process to warming. For example, while the decomposition of fresh litter responds strongly to warming temperatures, rate responses for mineral-associated soil carbon are less certain (Conant et al. 2011, Giardina et al. 2014, Bradford et al. 2016).

DRIVERS OF CARBON PROCESS RATES AND STORAGE

Canopy photosynthesis—the sum of leaf-level photosynthetic rates across a canopy—determines gross primary production and its components. External forcings (e.g., temperature, incident light, and phytotoxic gases such as ozone (O_3)) act on leaf-level photosynthesis and on gross primary production through effects on carbon uptake, allocation, and loss (Ryan 1991, Amthor and Baldocchi 2001, Baldocchi and Amthor 2001, Litton et al. 2007, Litton and Giardina

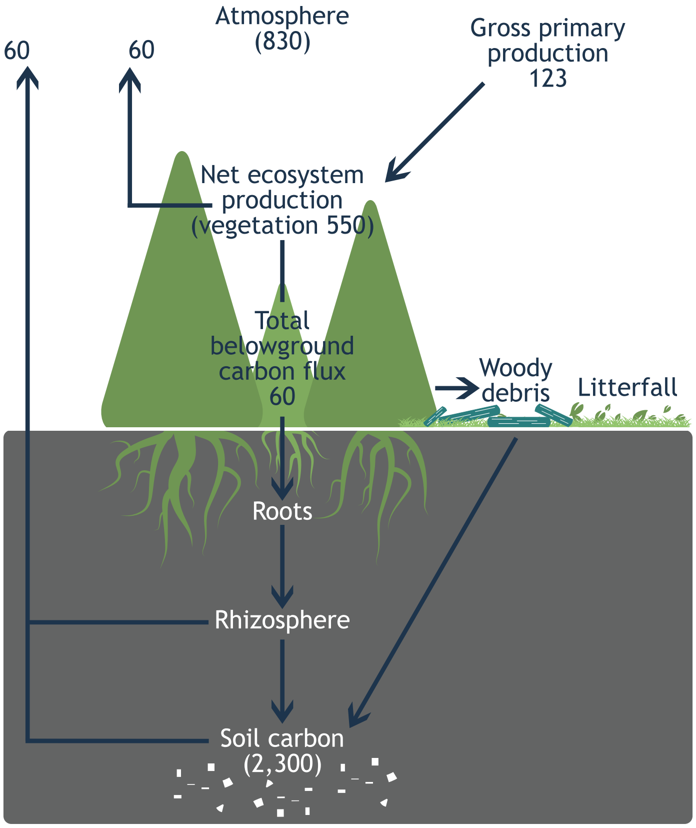

Figure 5. A depiction of the forest carbon cycle including both aboveground and belowground storage and flux terms. Carbon (Gt C) stocks are denoted in parentheses and shown in gigatons. Fluxes (Gt C per year) are associated with arrows and shown in gigatons per year.

2008, Bonan 2008, Giardina et al. 2014). While sunlight is a foundational driver of leaf and canopy photosynthesis, temperature and moisture are forcing variables that are increasingly receiving attention because they exert strong influences on plant and ecosystem productivity. These variables are changing for much of the planet—dramatically in some places (U.S. CCSP 2007). Under optimal moisture and sunlight, the response of canopy photosynthesis to warming is parabolic, rising to an often very plastic (seasonally and across species) maximum between 20 and 30 degrees Celsius. Below the optimum temperature, enzyme reaction rates limit canopy photosynthesis, while above the optimum temperature, warming causes cellular membranes to become less stable, alters the relative solubilities of CO_2 and O_2, and drives a steep increase in photorespiration, all of which cause canopy photosynthesis to decline (Baldocchi and Amthor 2001). Because water is assimilated with CO_2 during photosynthesis to produce carbohydrates, water availability to plants is a strong determinant of gross primary production. Longer term patterns in water-availability shape plant communities, composed of species that are associated with traits adapted to water and temperature conditions of a location. For a given species, especially long-lived trees, reductions in water availability due to climate variability, episodic drought, or longer term baseline shifts in precipitation, can cause a series of diurnal to seasonal to inter-annual responses that affect gross primary production. In wet climates, drying can result in increases in gross primary production (Luyssaert et al. 2007) because of factors such as soil saturation and the increases in sunlight that might accompany reduced cloud cover and drying of a normally wet site (Nemani et al. 2003), though these trends can be reduced over time (Zhao and Running 2010).

For areas that are more mesic, drying can cause stomatal closures, enhance photorespiration rates, and directly constrain leaf-level photosynthesis (Baldocchi and Amthor 2001). Similarly, site hydrology is regulated by geomorphology, which in turn can modify the effect of macro-climate on the amount of water available to plants. On the scale of season, growing season length is a strong determinant of total canopy uptake (Baldocchi et al. 2001); total assimilated carbon shows a strong linear relationship with the time period during which temperature and moisture conditions are favorable for photosynthesis. Clearly, multiple factors can vary over the course of a season, including sunlight in nonequatorial regions, leaf area and intercepted sunlight, canopy nutrient status, and light, in addition to temperature and soil moisture. Further, physiological functioning of plants can show strong capacity to acclimate to changing temperatures over timeframes ranging from seasonal to decadal, and longer when species shifts are considered. For this reason, studies that rely on surrogates to understand the effects of climate warming (e.g., variation across latitude of elevation to achieve a gradient in mean annual temperature, variation across season to achieve a warming sequence, or variation between years to achieve annual temperature comparisons) may only capture a portion of the effects resulting from warmer air and soil temperatures. For example, in the case of "spring warm up," temperature effects on ecosystem processes, especially plant ecophysiological changes, may be confounded by changes to light regimes, leaf area, and fine-root length. Projecting "temperature" interpreted spring warm up functions onto forecasted warmer ecosystems of the future could lead to significant errors.

Atmospheric chemistry also affects plant and ecosystem productivity. Increasing levels of atmospheric CO_2 can stimulate gross primary production and carbon sequestration, although how that carbon is allocated to aboveground and belowground carbon pools can depend on species and site conditions (King et al. 2005, Luo et al. 2004, Norby et al. 2005, Liu et al. 2005). These productivity gains are most likely the result of both direct stimulation of photosynthesis (Norby et al. 2005), as well as indirect effects on growing season length (Taylor et al. 2008a) and associated increases in resource-use efficiencies (Baldocchi and Amthor 2001). Conversely, gases such as ozone (O_3), which is also increasing across temperate and tropic regions, can have the opposite effect on plants (King et al. 2005). Ozone can cause damage to leaves, compromise growth, and reduce carbon storage, all of which can have cascading effects on soil carbon formation (Loya et al. 2003).

Vegetation species composition or genotype effects on ecosystem productivity can be significant. A foundational practice in forestry is tree selection and improvement, and gains in productivity have been substantial in the past century (Ryan et al. 2010). These species-level effects relate primarily to physiological trait differences across species or within species across genotypes. Another example of species effects on productivity include biological plant invasions where the invader increased productivity of a site by increasing the supply of limiting resources (e.g., through nitrogen fixation), by increasing stand-level capacity to fix carbon at the leaf and/or canopy level, or by altering disturbance regimes (Vitousek 1990, Binkley and Fisher 2013, Peltzer et al. 2010). In addition to leaf and canopy physiology, tissue chemistry (and the associated return of nutrients, detritus and associated compounds to soil), plant allocation patterns, and resource-use efficiencies can vary dramatically across species occupying the same sites (Gahagan et al. 2015).

Perhaps the strongest constraint on carbon storage on site is disturbance (Pregitzer and Euskirchen 2004; Ryan et al. 2010). Disturbance ranges from single tree mortality to tree falls to stand and landscape-scale events such as ice storms, blowdowns, or wildfire. As disturbances increase in extent from single trees to whole stands to entire landscapes, the impact on landscape-scale carbon stocks also increases (Ryan et al. 2010). Similarly, as disturbance duration and intensity increase, the likelihood of carbon loss also increases—for example, harvest intensity, windstorm duration, or fire severity. Finally, the disturbance return interval can influence maximum storage achievable at a site. For example, very short return interval disturbances, such as annual tall grass prairie fires, can prevent a system from succeeding from grassland to forest, whereas long return intervals can allow for old growth forest conditions that store among the largest quantities of aboveground biomass in the terrestrial biosphere.

SUMMARY

In conclusion, there are five basic points to consider concerning forest carbon cycling. First, controls on carbon fluxes and storage (e.g., temperature, rainfall, seasonality, soils, hydrology, nutrients, and disturbance history) vary across time and space, and so carbon fluxes and storage also vary across time and space. Predictive numerical models now capture these drivers reasonably well, although refinement is required belowground and in response to atmospheric changes. Second, aboveground and belowground carbon fluxes tend to increase where the climate of sites is warmer and wetter. Temperature and moisture exert fundamental controls on site productivity, and so spatial and temporal variation in these drivers will drive variation in productivity. Third, aboveground and belowground carbon storage are higher in locations where it is warmer and wetter, but significant work must be conducted to elucidate the independent and interactive effects of these two drivers. Fourth, significant work must be conducted to isolate independent and interactive effects and further demonstrate that soil carbon increases in locations where it is wetter and generally decreases in warmer locations. Finally, management, including nutrition and disturbance management, as well as species or genotype selection, can have large effects on both fluxes and storage.

Chapter 3: Carbon Monitoring and Accounting

From 1990 to the present, the U.S. Department of Agriculture (USDA), Forest Service has been responsible for monitoring and reporting greenhouse gas emissions and removals from forest land in the United States each year. This requirement is a component of the Inventory of U.S. Greenhouse Gas Emissions and Sinks prepared by the U.S. Environmental Protection Agency in accordance with the United Nations Framework Convention on Climate Change (UNFCCC). Since global efforts to track greenhouse gas emissions began in the early 1990s, Forest Service researchers have helped build the foundation for this evolving field. Significant contributions to carbon-pool science over the last 25 years include integrating Forest Inventory and Analysis (FIA) field data and data on harvested wood products into the greenhouse gas inventory process and developing robust estimation tools and techniques. This section provides an overview of forest carbon inventory at the entity and national scales.

The Intergovernmental Panel on Climate Change Good Practice Guidance (2006) for Land Use, Land-Use Change, and Forestry (LULUCF) presents two basic approaches to carbon accounting—the stock difference method and the gain-loss method. As monitoring technology and resources vary across UNFCCC signatory nations, guidance recommends using either method or a combination of methods that provide the highest levels of certainty in the context of national capacity. With the stock difference method, mean annual net carbon emissions or removals for land subject to human activities are estimated as the ratio of the difference in carbon stock estimates at two points in time and the number of intervening years. With the gain-loss method, total net emissions are first estimated as the sum of activities of products of activity area estimates and emissions factor estimates for those activities. The total is then divided by the number of intervening years to estimate mean annual net emissions or sequestration. In the United States, both approaches are used to estimate carbon stock changes for different land-use categories (e.g., croplands versus forest land) depending on the availability of inventory data. Where inventory data exist (for example, in the United States, the National Forest Inventory produces what are commonly called FIA data), the stock difference approach is used. When inventory data are sparse, the gain-loss method or a combination of the two methods is used.

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SYSTEM BOUNDARIES AND SCALE

The inventory and accounting methods described in this section have been modified from national scale guidelines (IPCC 2006, Smith et al. 2006) for use at the entity level. An entity may be defined as a single property, and the system boundary is the extent of that property. There will be carbon fluxes across the system boundary (e.g., lateral transfer of carbon in the soil). Harvested wood products, however, are not typically estimated because there are limited data on these complex processes. Trees on a property may not fit the definition of a forest (i.e., land adequately stocked with trees meeting minimum area, width, and tree cover requirements) creating complexities in inventory and accounting. Methods from multiple land-use categories (forest land, cropland, and grassland) will likely be required—with care taken to avoid double counting—to obtain a comprehensive estimate of carbon stocks and stock changes for the entity (for complete descriptions of accounting techniques for different land-use categories, see Eve et al. 2014).

Unlike annual crops, which are considered by the IPCC (2006) and the U.S. Environmental Protection Agency (U.S. EPA 2016) to be ephemeral with no net emission to the atmosphere (West et al. 2011), perennial woody crops have the potential to sequester large amounts of carbon per unit area (Dixon et al. 1994, Kumar and Nair 2011). To account for carbon stocks and stock changes in forest land or woodlands, measurements collected as part of a field inventory may be used to meet the necessary data requirements for carbon accounting purposes. In most cases at the entity scale, repeated annual remeasurements are not practical nor are the changes in carbon stocks sufficiently different from year to year to support annual remeasurements. Instead, projection models and/or look-up tables from the IPCC (2006) and USDA Forest Service (2014a) may be used to account for temporal changes in vegetation and associated ecosystem pools when data collection is not feasible at these smaller spatial scales.

Summary of Inventory and Data Requirements

Inventories of natural resources contribute to the accounting of various products and/or services (e.g., carbon sequestration) those resources provide. In ecosystems, carbon pools may be broadly or narrowly defined depending on the size of the entity, type of management practice, and available data (Eve et al. 2014). When there are limited data available for a property, perhaps only aboveground live biomass associated with live trees may be evaluated in terms of changes in associated carbon pools over time. In contrast, if there are abundant data available for the diversity of forest ecosystem components, significant resources are available, and—it is of practical interest—the biomass for all forest carbon pools can be monitored.

Estimation of Carbon Stocks and Stock Change

Obtaining sound estimates of carbon stocks and stock change in ecosystems requires balancing data availability with the owner or manager’s resources and needs. Explicitly establishing system boundaries and the carbon in ecosystem pools to be included in the accounting framework helps identify possible gaps or overlaps between pools or methods, particularly when combining methods across land-use categories. Furthermore, consistent definitions and estimation methods must be used for each pool and across time intervals to ensure valid estimates of carbon stock change.

CARBON ACCOUNTING AT THE NATIONAL LEVEL

This section provides an overview of the assessment of carbon emissions and removals resulting from the uses and changes in land types and forests in the United States, with emphasis on forest ecosystems. The IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006, IPCC 2014b) recommends reporting fluxes according to changes within and conversions between land-use categories termed forest land, cropland, grassland, settlements, wetlands, and other lands.

Land Representation

In accordance with IPCC (2006) guidelines for reporting greenhouse gas fluxes to the UNFCCC, the United States uses a combination of approaches and data sources to: (1) determine areas of managed and unmanaged lands (i.e., land influenced by human activities), (2) apply consistent definitions for the land-use categories, and (3) account for greenhouse gas fluxes on all managed lands (U.S. EPA 2016). Aspatial data from the Natural Resources Inventory (NRI) and FIA programs are used with spatially explicit time series land-use data from the National Land Cover Database (NLCD)(Jin et al. 2013) to provide a complete representation of land uses and land-use change for managed lands. In general, land in the United States is considered managed if direct human intervention has influenced its condition and all other land is considered unmanaged (largely comprised of areas inaccessible to society due to the remoteness of the locations; U.S. EPA 2016).

NATIONAL ACCOUNTING DATA SOURCES

The different land-use categories are monitored by national inventory programs that focus primarily on forest land and agricultural lands. Since certain management practices (e.g., agroforestry) may not meet the definitions of the different land uses, they may not be monitored by the national inventory programs (Perry et al. 2005) and thus not accounted for in national carbon monitoring initiatives. That said, there are several pilot studies currently underway evaluating novel approaches to monitoring remote areas (for example, in interior Alaska), urban areas, and tree cover in agricultural landscapes (Liknes et al. 2010, Meneguzzo et al. 2013).

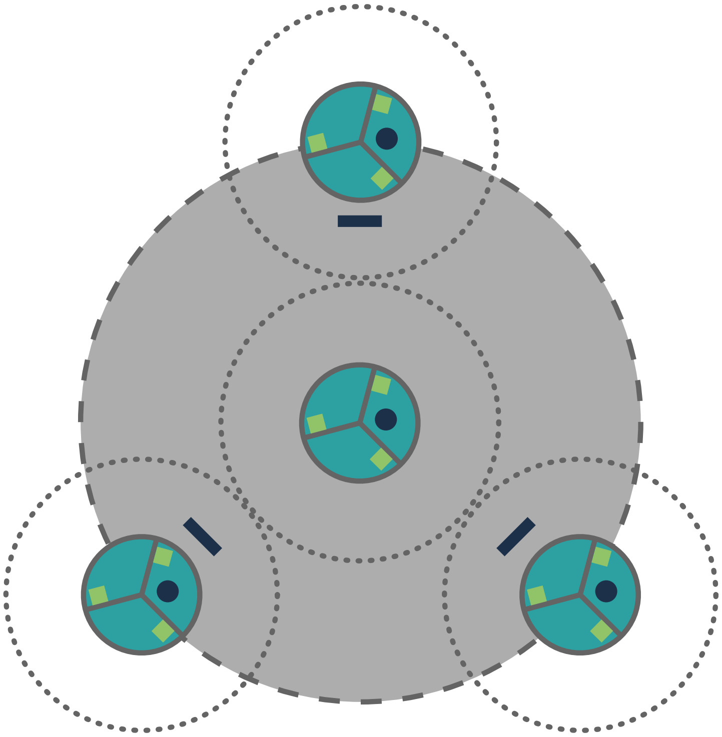
Forest Inventory and Analysis

Conducted by the Forest Service since 1930, the FIA program is a statistically based survey for the United States, and the official source of information used to assess the status, trends, and sustainability of America's forests. The FIA program employs a multiphase inventory, with each phase contributing to the subsequent phase. First, current aerial photography and/or remotely sensed data products—such as National Agriculture Imagery Program (USDA FSA 2008) and NLCD (Jin et al. 2013)—are used in a prefield process to examine all sampling points (i.e., plot locations) to determine whether a forested condition exists at each point. Next, each sample point is assigned to a stratum using imagery or thematic products obtained from satellites, such as those used by NLCD (Homer et al. 2007). A stratum is a defined geographic area (e.g., State or estimation unit) that includes plots with similar attributes; in many regions, strata are defined by predicted percent canopy cover.

Base intensity permanent ground plots are distributed approximately every 2,428 hectares across the 48 conterminous States of the United States, as well as across Hawaii and southeast and south-central Alaska. Each permanent ground plot comprises a series of smaller fixed-radius (7.32 meter) plots (i.e., subplots) spaced 36.6 meters apart in a triangular arrangement with one subplot in the center (fig. 6). Tree- and site-level attributes—such as diameter at breast height and tree height—are measured at regular temporal intervals on plots that have at least one forested condition defined in the prefield process (USDA Forest Service 2014b). On every 16th base intensity plot, distributed approximately every 38,848 hectares, additional ecosystem attributes (e.g., soils, downed dead wood, litter) are measured (Bechtold and Patterson 2005). This information is used to estimate carbon stocks and stock changes on managed forest land in the United States. Details on the methods and models used to obtain estimates of forest carbon stocks are available in Smith et al. (2006) (understory biomass), Domke et al. (2011) (standing dead trees), Woodall et al. (2011) (live aboveground biomass), Domke et al. (2013) (downed dead wood), Domke et al. (2016) (litter), and Domke et al. (2017) (soil organic carbon).

Natural Resources Inventory

The NRI is the official source of data on all land uses on non-Federal lands in the conterminous United States and Hawaii (except forest land) and is also used as the resource to determine the total land base for the conterminous United States and Hawaii (USDA NRCS 2016). The NRI is a statistically based



●	Subplot	24.0 ft (7.32 m) radius
●	Microplot	6.8 ft (2.07 m) radius
○	Annular plot	58.9 ft (17.95 m) radius
●	Lichens plot	120.0 ft (36.60 m) radius
🟩	Vegetation plot	1.0 square meter area
▬	Soil sampling	(Point sample)
▬	Down woody debris	24 ft (7.32 m) transects

Figure 6. Forest Inventory and Analysis plot design. Adapted from USDA Forest Service (2005).

survey conducted by the USDA Natural Resources Conservation Service and is designed to assess soil, water, and related environmental resources on non-Federal lands. The NRI survey utilizes data obtained from remote-sensing imagery and field visits to provide detailed information on land use and management, particularly for croplands and grasslands, and is used as the basis to account for carbon stock changes in agricultural lands.

National Land Cover Database

The NLCD, a product of the Multi-Resolution Land Characteristics (MRLC) consortium comprised of several Federal agencies, is used as a supplementary database to account for land use on Federal lands not included in the NRI and FIA databases. The NLCD land-cover classification scheme, available for 1992, 2001, 2006, and 2011, has been applied over the conterminous United States (Homer et al. 2007), and also for Alaska and Hawaii in 2001. For the conterminous United States, the NLCD Land Cover Change Products for 2001 and 2006 were used in order to represent both land use and land-use change for Federal lands (Fry et al. 2011, Homer et al. 2007). The NLCD products are based primarily on Landsat Thematic Mapper imagery. The NLCD is strictly a source of land-cover information and does not provide the necessary site conditions, crop types, and management information from which to estimate carbon stock changes on those lands.

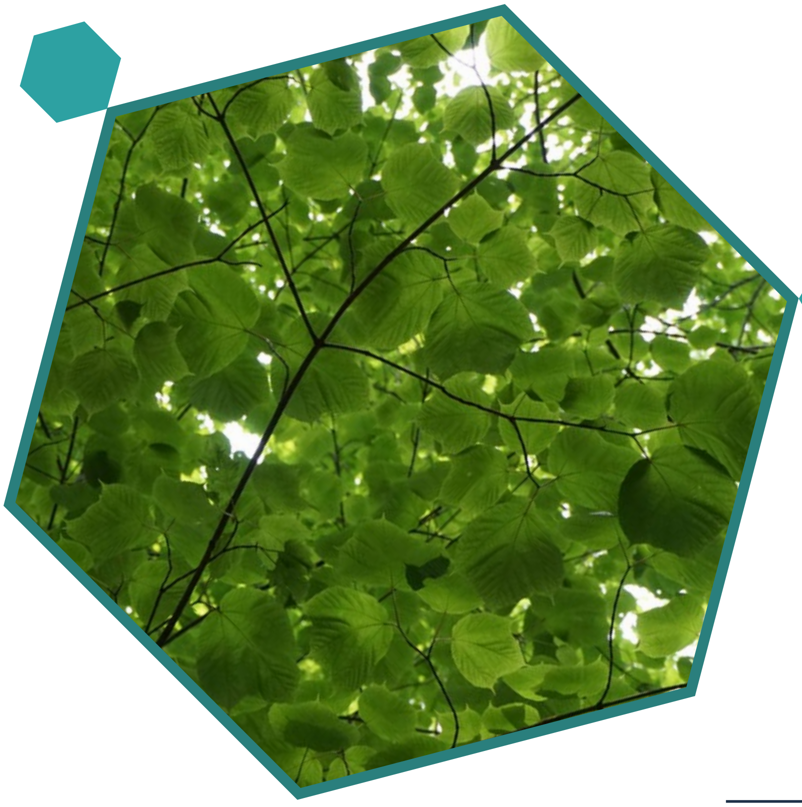
UNCERTAINTY AND VARIABILITY OF ESTIMATES

Uncertainty (i.e., the level of confidence that an estimate is reflective of the actual value) associated with greenhouse gas estimates in forest ecosystems is an important aspect of decisionmaking for landowners, land managers, and policymakers. There are many factors that contribute to uncertainty in greenhouse gas estimation, including measurement and sampling error, modeling error, as well as interpretation of the protocols followed. Monte Carlo methods are often recommended for estimating the statistical uncertainty associated with greenhouse gas estimates (IPCC 2000). While the methods may vary based on data availability, generally simulations are run many times (e.g., 1,000 to 10,000) to obtain a probability distribution around the greenhouse gas estimate of interest that can then be used to estimate statistical uncertainty.

These methods can be applied at any scale and the uncertainty associated with the estimates should reflect the sampling methods, measurement techniques, and models used. Strategic-level forest inventory data like that collected by the FIA program is designed to meet precision standards at the State level. Using FIA data at finer spatial scales can increase the potential error associated with estimates, and so it is generally inappropriate to use FIA data at spatial scales finer than the county level.

TOOLS

There are several tools and data sources to help estimate carbon stocks and stock changes in the United States. The EVALIDator[1] program allows users to produce a large variety of population estimates and their sampling errors based on the current FIA database. The Forest Inventory Data Online[2] gives users access to the FIA database to generate tables and maps of forest statistics through a web browser without having to understand the underlying data structures. More advanced users can also download FIA, including estimates of carbon stocks for all IPCC carbon pools at the FIA DataMart,[3] directly. There is also a national data translator to convert FIA data into a Forest Vegetation Simulation[4] input database. The database is a family of forest growth simulation models. Based upon a body of scientific knowledge developed from decades of natural resources research and experience, the database includes a system of highly integrated analytical tools. In terms of desktop applications, the Carbon On-Line Estimator[5] allows users to examine carbon characteristics of any forest land area within the continental United States. Smartphone applications (e.g., http://forestcarbonx.umn.edu/) have been developed that enable estimation of forest carbon attributes within user-defined radii based on a phone's location.



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[1] http://apps.fs.fed.us/Evalidator/evalidator.jsp

[2] http://apps.fs.fed.us/fia/fido/index.html

[3] http://apps.fs.fed.us/fiadb-downloads/datamart.html

[4] http://www.fs.fed.us/fmsc/fvs/

[5] www.ncasi2.org/COLE/index.html

Chapter 4: Carbon and Land Management

Terrestrial ecosystems, including forests and grasslands, play an important role in sequestering carbon dioxide (CO_2), thereby helping to remove it from the atmosphere and lessening the effects of anthropogenic climate change (U.S. CCSP 2007, USDA 2011, IPCC 2013). There are a number of greenhouse gas mitigation actions that can help to reduce the effects of climate change by reducing greenhouse gas sources and enhancing carbon sinks in forests and grasslands (Birdsey et al. 2000, U.S. CCSP 2007, Millar et al. 2012). Ecosystem carbon is of particular interest because of the importance of CO_2 and methane (CH_4) as important greenhouse gases, as well as the ability of ecosystem vegetation to absorb and sequester CO_2 (Murray et al. 2005, USDA 2011). Land management actions can also affect the emissions of nitrous oxide (N_2O)—another very potent greenhouse gas—although the role of forest and land management is small regarding this compound.

Forests and grasslands are managed for many different objectives and a variety of goods and services, and may include timber, range, water, recreation, and wildlife. The amount of carbon absorbed and stored within a particular ecosystem is affected by land-use change, management activities, disturbance, the use of harvested wood, and climate. Carbon may be of interest in developing management plans and options, but rarely is it the primary management objective. This chapter provides information to support the integration of carbon considerations into land management, particularly in the context of carbon as just one of multiple management objectives. This chapter describes land management options for carbon management (i.e., greenhouse gas mitigation), suggests considerations for integrating carbon as a management objective, and outlines challenges for accounting for the full effect of management on forest and grassland carbon.

FOREST MANAGEMENT FOR CARBON BENEFITS

When considering carbon in the context of land management activities, it is necessary to consider the overall management objectives associated with a piece of land, the carbon stocks in different pools, and the flows of carbon between these pools. Carbon accrues in plants and soil. In forests, carbon is stored in live trees, standing dead trees, downed wood, the forest understory, and soils and can be transferred among these different pools and to the atmosphere (see earlier sections for additional discussion of

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forest carbon pools and fluxes). The industrial side of the forest carbon cycle should also be considered, as carbon can also accrue in wood products and substitute for fossil fuel-based products (Gower 2003) (fig. 7).

Within ecosystems, carbon management frequently focuses on determining the amount of carbon stored in biomass and soil, as well as the rate new carbon is being sequestered into biomass from vegetation growth. The determination of management impacts on carbon cycling depends heavily on the scope of the analysis being undertaken (Harmon 2001, McKinley et al. 2011, Millar et al. 2012), which can focus on fine spatial scales like an individual stand to broad scales covering an entire landscape, region, or continent. The spatial scale of analysis when evaluating carbon outcomes often directly impacts the conclusions made about forest carbon stocks, as does the temporal scale (Harmon 2001). When looking at fine spatial scales and short timeframes, harvest may remove a large portion of the carbon within the system. However, across larger spatial scales and time periods, harvest impacts to carbon stocks may be minimal relative to total carbon within the system (fig. 8).

Harvested wood can be used to create products ranging from short-lived paper products to durable wood products that can last more than 100 years, as well as wood for energy (Bergman et al. 2014, Skog 2008, Skog and Nicholson 2000). Ultimately, the carbon stored in wood products is returned to the atmosphere through decomposition or combustion, although the time needed for this return can vary widely based on the use and longevity of materials made from harvested wood. Additionally, there are different timeframes associated with different

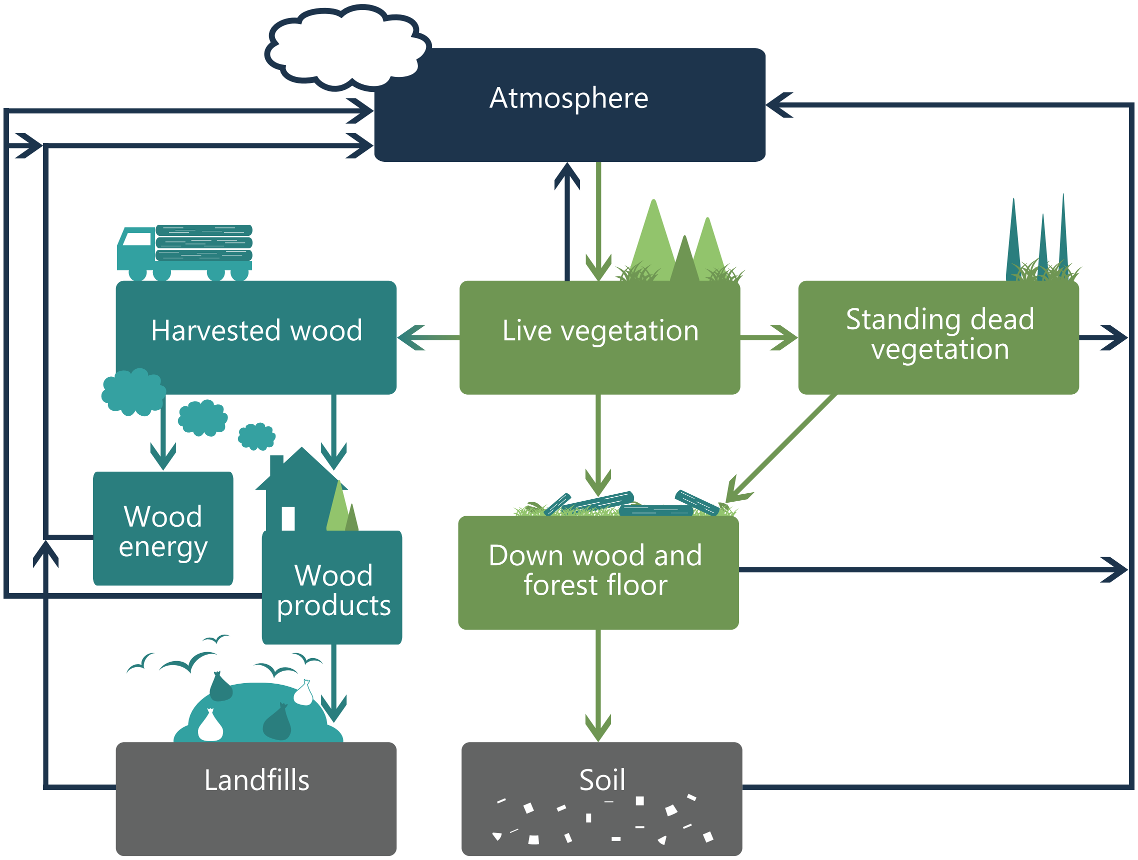

Figure 7. The forest sector carbon cycle includes forest carbon stocks and carbon transfer between stocks. Adapted from Heath et al. (2003) and USDA (2011).

carbon pools that also need to be considered when evaluating how an action may affect carbon stocks and fluxes. For example, the combustion of wood for energy releases carbon to the atmosphere immediately, whereas carbon released from the decomposition of wood in the forest floor may take years to decades. Because of the dynamics of forest growth, management actions potentially have lasting effects years, decades, or even centuries into the future (Harmon et al. 1990, Perez-Garcia et al. 2007).

Because the system boundaries used in carbon analyses vary widely across studies, it can be difficult to compare strategies for mitigation (Millar et al. 2012). The complexity of the forest carbon cycle—including spatial and temporal dynamics, interactions among forest carbon pools, and natural and human influences—underscores the importance of using methods that consider the net effects of management activities on carbon stocks and greenhouse gas emissions to the atmosphere (Brunet-Navarro et al. 2016). The long-term nature of forest growth may mean that management actions that emit carbon to the atmosphere in the short term may be able to enhance forest growth and provide greenhouse gas mitigation benefits over a longer period (Perez-Garcia et al. 2007). Tools like the Forest Vegetation Simulator can simulate forest vegetation response to management and estimate the change in carbon stocks over time (via the Fire and Fuels Extension), but does not include carbon emissions associated with management operations, such as fuel for equipment use or transportation. Data-intensive approaches, such as life-cycle assessment, attempt to quantify the environmental impacts, including carbon emissions, of a product or process by factoring in all inputs and outputs of a system (Bergman et al. 2014, Helin et al. 2013).

Maintain or Increase Forest Coverage

Carbon storage is typically greater within forest ecosystems when compared to lands that are used for settlements or agriculture (Pacala et al. 2007). Natural ecosystems themselves also have a great degree of variation in how much and for how long carbon is stored based on the interactions among climate, soils, vegetation, and past disturbance in a particular location (Carvalhais et al. 2014) (fig. 9). For this reason, actions to maintain the integrity of forest ecosystems or increase their extent will generally have positive benefits for greenhouse gas mitigation (Birdsey et al. 2000, Millar et al. 2012).

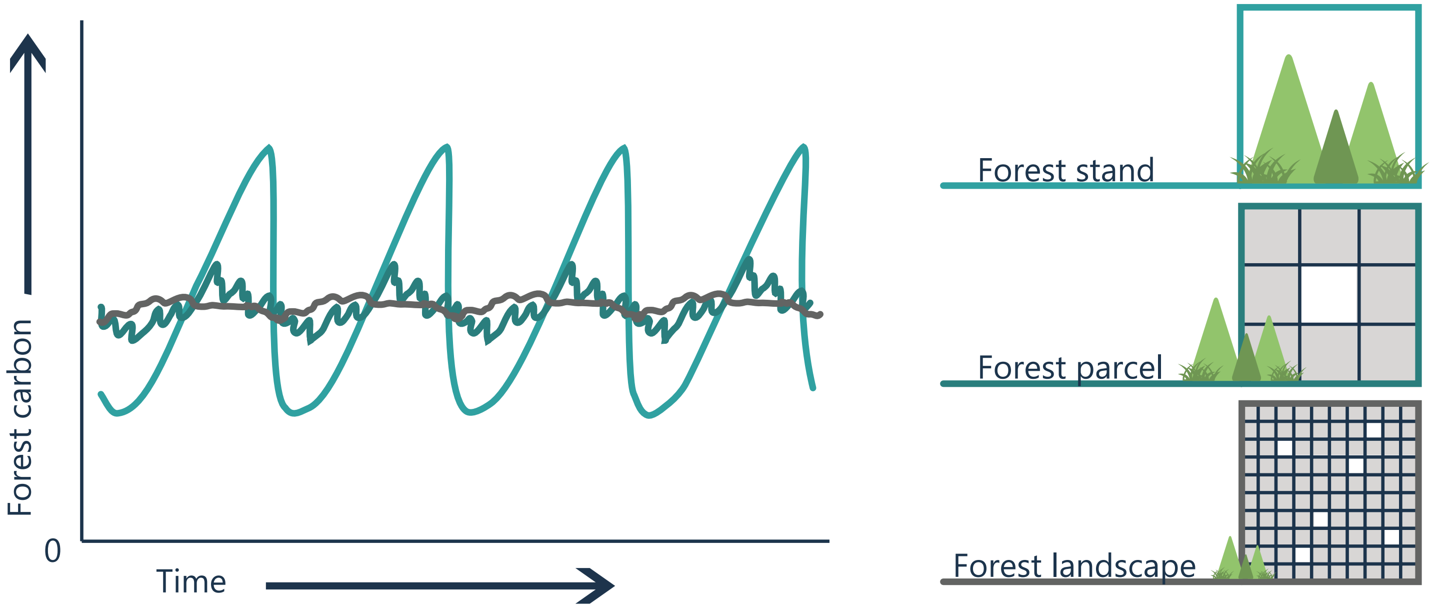

Figure 8. The influence of spatial and temporal scales on forest carbon storage. Adapted from Bowyer et al. (2012) and McKinley et al. (2011).

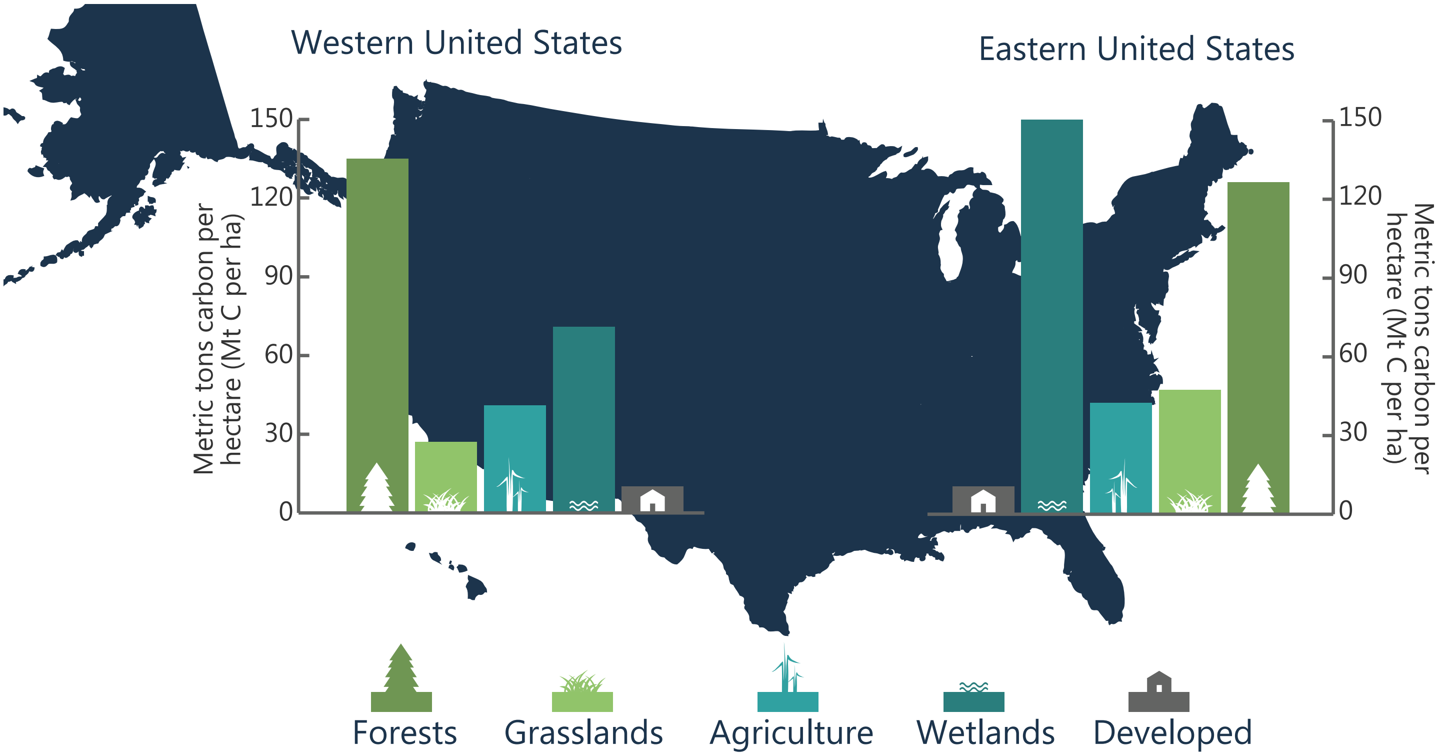

Figure 9. Carbon stocks within different ecosystems in the Eastern and Western United States shown in metric tons per hectare (Mt C per ha). Data from Liu et al. (2012) and Liu et al. (2014).

Avoided Conversion of Forest to Nonforest Use

Although the conversion of forest to nonforest use (i.e., deforestation) is often discussed as an international issue, a substantial amount of forested land within the United States is converted to other uses each year. Between 1982 and 2012, more than 1 million acres of U.S. forest land were converted each year to development, agriculture, or other purposes (USDA NRCS 2015). Although this loss is more than accounted for by a gain of more than 1.3 million acres of nonforest area that is converted to or reverts back to forest each year (resulting in a net gain of forest acres)(Birdsey 2012); converting land to a nonforest use removes a very large amount of carbon at one time. Because mature forest stands are more likely to be carbon rich from the high volume of tree biomass, recovery takes a very long time through afforestation (Murray et al. 2005). Harvesting biomass can quickly remove much of that accumulated biomass carbon. Further, soil carbon generally declines after deforestation from accelerated decomposition of organic matter such as litter and tree roots (Murray et al. 2005). Efforts to maintain forest cover and prevent conversion to nonforest uses help to maintain the ability of that land to sequester carbon into the future, thereby preventing emissions and also increasing the potential for additional sequestration.

Increase Afforestation

Just as avoiding forest losses through deforestation and conversion to other land uses helps maintain both carbon stored in forests and the capacity to continue sequestering additional carbon, afforestation increases the potential for land to store carbon by converting nonforest land to forest. For many decades, the trend in the United States has been toward increasing coverage of forest land as ecosystems recover from past clearing and disturbance and marginal agricultural lands are taken out of production (Birdsey et al. 2006). Afforestation can increase sequestration within the United States at an average of about 2.2 to 9.5 metric tons of carbon per acre per year for 120 years (Birdsey 1996, Congressional Budget Office

2007). Afforestation may be more feasible on lower value lands that are marginal for agriculture or other activities (Stanturf et al. 1998), with benefits for both biomass and soil carbon stocks (Chang et al. 2014).

Maintain and Increase Forest Carbon Stocks

Forest carbon stocks are closely tied to forest biomass, so factors that increase tree growth rates will subsequently increase rates of carbon storage within forests (McKinley et al. 2011, Ryan et al. 2010). For example, nitrogen deposition from industrial and agricultural activities has increased soil nitrogen availability, allowing trees to more effectively increase carbon capture and contributing to the capacity of existing forests to sequester carbon (Nadelhoffer et al. 1999). Additionally, higher atmospheric CO_2 levels, changes to patterns of temperature and rainfall, and changing forest management strategies all contribute to higher rates of carbon storage in existing forests (Ainsworth and Rogers 2007, Cole et al. 2010, Franks et al. 2013). There is some uncertainty, however, surrounding the capability of forests to continue to assimilate additional CO_2 with additional changes in the climate (Bellassen and Luyssaert 2014). Forest management activities can be used to increase the amount of carbon that is sequestered in forests, as well as the amount of carbon stored in wood products (Birdsey et al. 2000). The amount of additional carbon that can be sequestered depends greatly upon the condition of the forest (e.g., forest type, age, health) and the forest management practice in question, making it important to take into account change to carbon stocks across the entire system to assess trade-offs between different pools (fig. 7). The forest management practices described below generally reduce carbon losses from forests or increase carbon gains in forest and wood products, although many practices have the potential to do both.

Decrease Forest Carbon Loss

Decreasing the intensity of forest harvest is one way to decrease carbon losses to the atmosphere (McKinley et al. 2011, Ryan et al. 2010). Across diverse forest systems, the “no harvest” option commonly produces the highest forest carbon stocks (Creutzburg et al. 2015, Nunery and Keeton 2010, Perez-Garcia et al. 2007). Managed stands typically have lower levels of forest biomass than unmanaged stands, even though the annual rate of sequestration may be higher in a younger forest. In managed forests, reducing harvest intensity, lengthening harvest rotations, and increasing stocking or retention levels will generally increase the amount of carbon stored within forest ecosystem carbon pools in the absence of severe disturbance (D'Amato et al. 2011, Harmon 2001, Harmon and Marks 2002, McKinley et al. 2011, Taylor et al. 2008b). One study in the Pacific Northwest modeled different levels of harvest in Douglas-fir/hemlock forest and found higher levels of residual forest carbon under less-intense management regimes (Harmon et al. 2009). Another study in the Northeast United States looked at both even- and uneven-aged management practices in northern hardwood forests and found that less-frequent harvests and greater levels of structural retention (e.g., residual trees) resulted in increased forest carbon stocks (Nunery and Keeton 2010). The results of modeling studies are also consistent with observations in experimental studies (D'Amato et al. 2011, Powers et al. 2011).

Carbon losses can also be reduced by limiting emissions associated with management, which can come from a number of sources. Forest harvest can cause disturbance to the ground, releasing carbon from soils and the forest floor (Nave et al. 2010). This effect is generally transitory, but varies with the degree of disturbance (Nave et al. 2010). Mechanical treatments to thin forest stands can cause disturbance that leads to additional soil carbon losses through increased erosion (Schwilk et al. 2009, Stephens et al. 2012). Forest harvest also creates emissions from the operation of machinery used to implement forest harvest; these emissions vary widely based upon the size and type of machinery, as well as the specifics of silvicultural treatments (box 3).

Forest management may also be able to reduce carbon losses associated with disturbances. Wildfire in particular is an increasingly substantial source of CO_2 and other greenhouse gas emissions from U.S. forests. Annual greenhouse gas emissions from wildfires in the conterminous United States and Alaska ranged from 42 to 139 Mt of CO_2 equivalent during the period from 2010 to 2013 (U.S. EPA 2016). Fuel-reduction treatments can lower the risk of crown fires, which are more likely to lead to intense fire conditions that cause substantial carbon losses (Millar et al. 2012, Reinhardt et al. 2008, Stephens et al. 2012). Fuel-reduction treatments lower the density of the forest stand, and, therefore, reduce forest carbon. Some studies suggest that fuel-reduction treatments create carbon benefits over time by increasing the growth of the residual stand and reducing risk of catastrophic fire (Boerner et al. 2008, Finkral and Evans 2008, McKinley et al. 2011). The results of studies to date, however, are divided as to whether this benefit can be realized. Prescribed fires also result in the release of greenhouse gas emissions, which need to be accounted for when considering the relationship between fire and carbon (Hurteau and North 2009, Wiedinmyer and Hurteau 2010). Additionally, carbon emissions from prescribed fire, the machinery used to conduct treatments, or the production of wood for bioenergy may reduce or negate the carbon benefit associated with fuel treatments, especially when treatments are repeated (Campbell et al. 2012, Hudiburg et al. 2013, Loehman et al. 2014). Further, there are uncertainties in predicting the actual occurrence of wildfire and its impacts on forests due to an incomplete scientific understanding of ecological response to fire, of fire behavior response to treatments, and inability to predict fire occurrence at the stand level (McKinley et al. 2011, Thompson and Calkin 2011).

Increase Forest Growth and Carbon Stocks

Many forest management actions may be used to increase the amount of carbon sequestered in forests and in wood products (McKinley et al. 2011, Ryan et al. 2010). Similar to the management activities described above that reduce losses of carbon from forests, carbon gains can be made in forests by increasing the rate of accumulation of new biomass, as well as by increasing the total amount of biomass. The ability of different management practices to increase forest growth will vary greatly by region and by forest type, and the increase in carbon will generally be proportional to increases in growth rates (Ryan et al. 2010). For example, plantations of southern pine can have increased yields through the combined use of improved seedlings, control of competing vegetation, and use of fertilizers (Ryan et al. 2010). Fertilization and irrigation of southeastern tree species can increase biomass growth by more than 100 percent (Albaugh et al. 2004, Coyle et al. 2016), but the carbon accumulation from enhanced growth would need to be balanced with the high levels of emissions associated with fertilizer production (Millar et al. 2012).

Forest managers who are working to enhance forest carbon sequestration by managing forests for increased growth also need to consider the relationship between carbon stored in the forest and carbon that is harvested to create wood products or energy, which are discussed in more detail in the next section. Increasing carbon stocks within the forest may or may not be great enough to balance the associated loss of carbon from harvested wood

BOX 3

Emissions From Forest Management Operations

Forest management activities can have a substantial influence on the amount of carbon stored in a forest, as well as what is available for use as wood products or bioenergy. The actual forest management operations also affect the size of the carbon benefit that can be gained. Operations such as tree harvesting, planting, fertilization, and trucking produce greenhouse gas emissions from the fossil fuel used to carry out these activities (Ingerson 2011). For example, one study that compared the carbon effects associated with different types of harvest found that the type of skidding machinery (e.g., grapple skidder, cable skidder, etc.) used to haul wood was more predictive of the net carbon flux of forest management activities than the primary silvicultural treatment (Mika and Keeton 2013).

that may have been stored in long-lived wood products or avoided fossil fuel emissions through bioenergy (Ingerson 2011, McKinley et al. 2011). It is also important for forest managers to consider the interactions between an increase in biomass and increasing risk of fires, insect damage, and disease, which can negatively impact multiple goods and services, including carbon.

Use of Wood-based Products and Energy

Management activities can have a substantial effect on greenhouse gas mitigation that extends beyond the carbon contained within forest ecosystems. Harvested wood goes into diverse forest products that continue to store carbon for the duration of their useful life (Skog 2008, Skog and Nicholson 2000). Forest management activities can also supply wood directly for energy, and waste materials from wood products manufacturing and processing can be recovered to produce power.

Carbon Storage in Harvested Wood Products

A substantial amount of carbon is stored in wood products. Differences in the type of wood product, as well as its production, use, and disposal, have substantial influences on the amount and duration of carbon storage. Where the goals of forest management include carbon benefits, product use and disposal is an important consideration. Standard methods are available for estimating the carbon that is sequestered in harvested wood products (Smith et al. 2006), and life-cycle assessment approaches can be used for more in-depth analysis of carbon gains and emissions (Bergman et al. 2014, IIngerson 2011, Perez-Garcia et al. 2007).

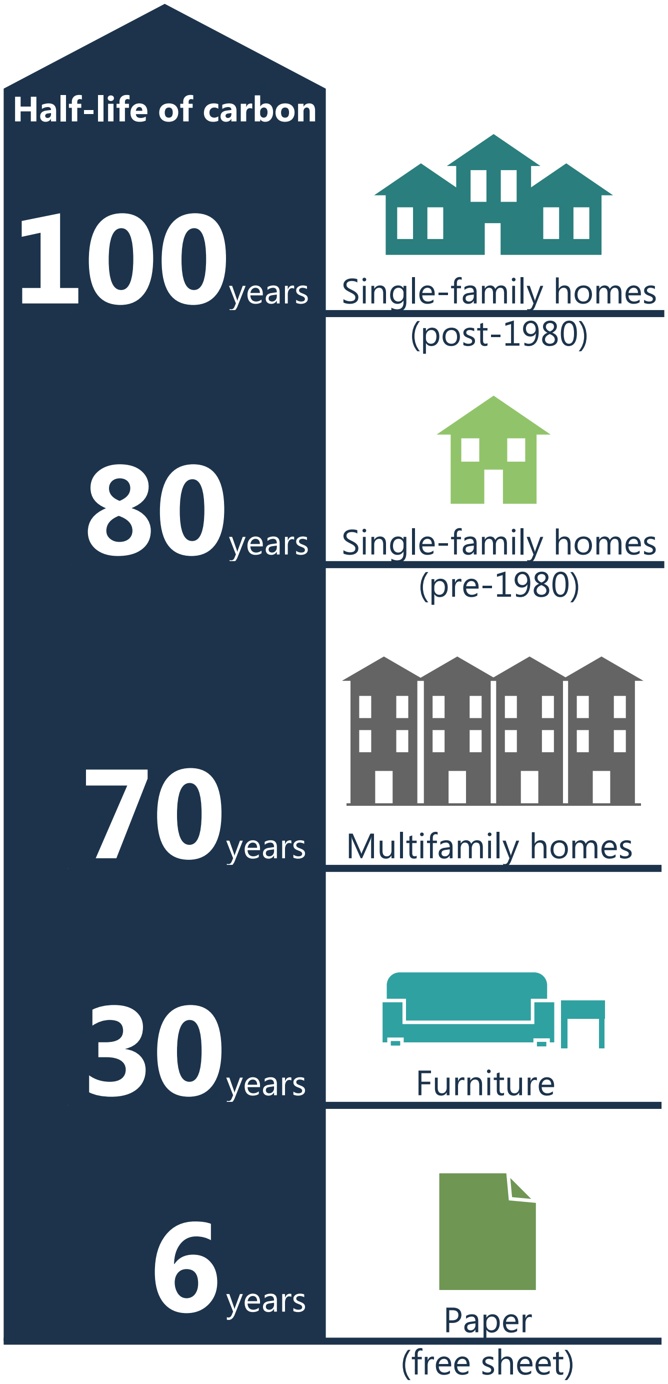

Figure 10. Assumed duration (years) of carbon sequestration in end uses of wood and paper. Data from Skog and Nicholson (2000).

In 2015, more than 2,600 million metric tons of carbon were stored in harvested wood products in the United States, which is equivalent to approximately 3 percent of the amount of carbon stored in U.S. forest lands (U.S. EPA 2016). Carbon stored in these wood products is further divided into two different pools: carbon that is stored in products currently in use and carbon that is stored in landfills (fig. 7) (Skog and Nicholson 2000, U.S. EPA 2016). Nearly 60 percent of the carbon in wood products is currently stored in products in use (U.S. EPA 2016). This category includes items such as paper, pallets, and the lumber used to construct buildings, each of which has a different decay rate (fig. 10). The remaining 40 percent of wood product carbon, from any source, is stored in landfills. Because materials in landfills are periodically covered, oxygen is not able to enter and facilitate decay; as a result, the total amount of carbon released from wood products in landfills is substantially reduced (Skog and Nicholson 2000). Further, of the carbon that is released, a greater proportion of it is in the form of methane due to anaerobic conditions (Skog and Nicholson 2000).

There are some ways that forest management can help to increase carbon storage in the harvested wood products pools. Emphasizing “durable” or “long-lived” wood products, such as lumber used for building construction can help to increase the overall lifespan of the product in use, as well as shift the mix of products toward those that decay less in landfills (Skog and Nicholson 2000). Wood products can also be used as substitutes for other materials that require greater fossil fuel inputs to produce, such as steel or concrete (Lippke and Edmonds 2006, Malmsheimer et al. 2008). For example, one study that compared the life-cycle emissions needed to build a single-family home using primarily wood, steel, or concrete construction materials found that the wood house had the least embodied energy, particularly compared to steel construction (Buchanan and Honey 1994, Glover et al. 2002). Although forest management can influence the species and size of trees available for wood products, larger scale policies and markets will largely drive the demand for particular products.

Bioenergy

Recent concerns regarding climate change and rising energy costs have dramatically increased interest in the use of renewable and alternative energies, including wood-based energy. While energy consumption from wood sources in the United States is currently greater than it was during much of the 20th century, the contribution of wood to the overall energy portfolio is small. In 2015, nearly 5 percent of U.S. energy consumption was from biomass sources (U.S. EIA 2016), about two-thirds of which is derived from forests (U.S. DOE 2011). The major sources of wood used for energy, including electricity, heat, and transportation fuel, include fuelwood (29 percent of forest biomass consumption), residues and pulping liquors from the forest products industry (60 percent), and wood municipal solid waste (10 percent) (U.S. DOE 2011). Wood sources may account for a greater portion of energy in the future; for example, one study evaluated the potential for the use of biomass feedstocks from forests to increase by 175 percent by 2030, with the majority of the increase coming from additional utilization and production of fuelwood (U.S. DOE 2011).

Forest management can be used to increase the amount of woody biomass that is available for energy use in a few different ways. One option is to increase the removal of logging residues—the woody material generated during forest harvest operations. These materials can include tree tops, branches, and stems that are unsuitable for use in the production of traditional forest products but can be used to generate energy as a replacement to fossil fuels (U.S. DOE 2011). One study identified that additional logging residues could displace as much as 17.6 million tons of carbon emitted from coal-fired power plants, or about 3 percent of total carbon emissions (Gan and Smith 2006). The greatest availability of these residues was in the Southeast and South Central regions of the United States (Gan and Smith 2006). While several studies point to the potential to use logging residues for bioenergy, the availability of these materials is heavily influenced by the financial costs of production relative to the sale price of biomass (Jones et al. 2013, U.S. DOE 2011). There are also concerns about the ecological effects of more intensive biomass removal from forests (Berger et al. 2013, Evans et al. 2013, Janowiak and Webster 2010).

There is also the potential to implement forest management activities for the purpose of generating wood for energy in addition to meeting other management goals. Biomass markets, where they exist, can provide additional opportunities for fuel-reduction treatments, noncommercial thinnings, and other silvicultural activities that do not contribute to the traditional forest-products industry. Fuel-reduction treatments may reduce the risk of large, high-intensity wildfires, thereby reducing the potential for emissions from wildfire and creating opportunities to substitute renewable forest-based energy for fossil energy (Finkral and Evans 2008, Malmsheimer et al. 2008).

Wood-based bioenergy is often compared favorably to fossil fuels and several renewable energies due to a relatively low amount of fossil fuel inputs and a smaller “carbon footprint” (Malmsheimer et al. 2008). Wood energy is sometimes talked about as being “carbon neutral” based upon the idea that any carbon that is released by the burning or use of wood for energy is recaptured through the sequestration of the forest as it regrows (Johnson 2009). The reality is more complex: The carbon effects associated with bioenergy production need to be evaluated to include the entire life cycle of energy production, as well as the longer term use and growth of the land used to produce the energy, relative to the business-as-usual use of fossil fuels (Haberl et al. 2012, McKechnie et al. 2010, Millar et al. 2012, Ter-Mikaelian et al. 2015). While many studies support the idea that woody bioenergy produced from sustainably managed forests can have carbon benefits over the long term, the degree of benefit is heavily influenced by factors that include the initial forest conditions, forest productivity, fossil energy from harvest operations and transportation, and the type of fossil fuel that is replaced by wood (Eriksson et al. 2007, Malmsheimer et al. 2008, Petersen Raymer 2006, Zanchi et al. 2012). A full accounting of the greenhouse gas benefit of forest bioenergy would include comparisons of forest carbon stocks for bioenergy versus a no-bioenergy scenario, as well as a full life-cycle assessment of the emissions used to produce forest bioenergy and for the displaced fossil fuel emissions (Jones et al. 2013, Ter-Mikaelian et al. 2015).

BOX 4

Urban Forests

Urban areas in the continental United States covered approximately 68 million acres in 2010, nearly 3.6 percent of the land area. Tree cover in urban areas averages 35 percent (Nowak and Greenfield 2012), making urban forests important stores of carbon in biomass. Between 597 and 690 million tons of carbon is stored within urban trees, with an annual sequestration rate of 18.9 million tons (Nowak et al. 2013). Overall carbon sequestration of urban forests is proportional to existing canopy cover and tree density within a city (McPherson 1994). Although rural forests typically sequester twice as much CO_2 as urban forests due to higher tree densities, urban trees can sequester more carbon per tree from higher growth rates (Jo and McPherson 1995). Enhanced carbon sequestration rates in urban trees may be explained by a combination of greater foliar biomass and reduced competition from lower tree densities, in addition to irrigation and fertilization. Urban forests also have additional benefits for carbon outside of sequestration. Trees in urban zones can have an important influence on carbon mitigation by reducing the energy requirements for building heating in winter due to wind protection and summer cooling from tree shading (Nowak et al. 2010). For example, three mature trees spaced around an energy efficient home can reduce annual air conditioning demand by 25 to 43 percent (Huang et al. 1987).

Managing urban forests for carbon capture often focuses on allocating resources to tree species that are most effective at long-term carbon storage. While growth rate is important for carbon benefits, tree species that are long lived, large in size, and have dense wood will store the greatest amounts of carbon, particularly relative to many short-lived, fast-growing species (McPherson and Simpson 1999). Proper site selection for individual species is also important for maximizing the carbon benefits of urban trees. Trees that are well adapted to their site will have higher growth rates and lower mortality rates, particularly in the initial years following establishment. Proper siting of trees in relation to buildings also optimizes the energy-saving benefits derived from summer shading or wind protection. For example, trees typically provide the greatest summer cooling benefits when placed on the west side of buildings.

GRASSLAND CARBON AND MITIGATION OPTIONS

Grasslands cover approximately 25 percent of the Earth's land surface (approximately 3.4 billion ha) and contain roughly 12 percent of the terrestrial carbon stocks (Adams et al. 1990, Ojima et al. 1993). Grasslands are dominated by herbaceous (nonwoody) vegetation and so—unlike forests—carbon within living aboveground vegetation is a small proportion of the total ecosystem carbon pool (fig. 11). Additionally, this aboveground biomass carbon is relatively short-lived due to harvest, grazing, fire, and senescence. In contrast, the perennial grasses that dominate grasslands are characterized by extensive fibrous root systems that often make up 60 to 80 percent of the biomass carbon in these ecosystems. This belowground biomass may extend several meters below the surface and contribute abundant carbon to soils, resulting in deep, fertile soils with high organic matter content. Because of this, soil carbon makes up approximately 81 percent of total ecosystem carbon found in grasslands (Adams et al. 1990). The tight linkage between soil carbon and belowground biomass results in similar responses of these carbon pools to variation in annual precipitation and temperatures at broad spatial scales. Because plant productivity is limited by precipitation in grasslands, carbon stocks are highest in regions where rainfall is the greatest, such as the tallgrass prairie in the humid temperate region of the United States. Similarly, grassland carbon stocks decrease with increasing annual temperatures due to greater evapotranspiration (Burke et al. 1989).

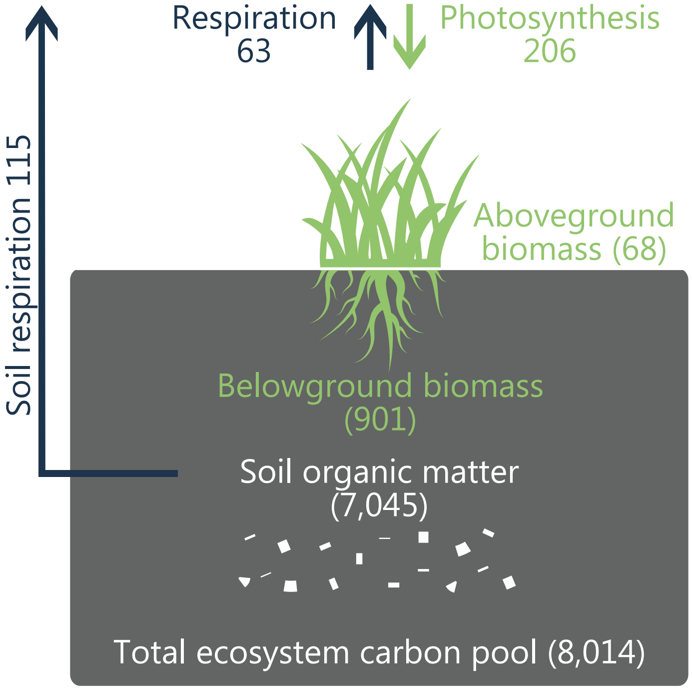

Figure 11. Carbon stocks and fluxes in in the shortgrass steppe ecosystem, Colorado. Carbon stocks are denoted in parentheses and shown in grams per square meter. Fluxes are associated with arrows and shown in grams per square meter per day. Data from Burke et al. (2008).

Grassland Carbon Losses and Land Degradation

Grasslands are used intensively for food and forage production globally because of their high natural soil fertility. Carbon stores within grasslands are sensitive to management and are thus vulnerable to losses in soil carbon. Land degradation—which is a long-term decline in plant productivity and the associated soil and water functions that support it—is widespread in grasslands in part due to soil carbon losses. More than 20 percent of the world's croplands are degraded, as are 20 to 25 percent of the grasslands (Bai et al. 2008). These losses in soil carbon are attributed to several factors, particularly decreased carbon inputs to the soil. Activities such as harvesting plant biomass significantly decreases the amount of carbon contributing to soil organic matter from removal of aboveground biomass. Likewise, changes of plant species to favor species with greater aboveground production—such as the conversion from natural grassland to cropland or improved pasture—significantly reduces the belowground biomass in roots as well (fig. 12).

Approximately 20 percent of the world's grasslands have been converted to cultivated crops (Ramankutty et al. 2008). Soil disturbance such as cultivation is a common management practice in annual row crop production, leading to greatly accelerated losses of organic matter. In the Midwest, many soils have lost 30 to 50 percent of carbon (25 to 40 metric tons of carbon per hectare) from conversion to agriculture (Lal 2002). These losses occur primarily through the disturbance of soil, which: (1) disrupts soil structure, exposing organic carbon to decomposition from soil microbes and invertebrates; and (2) increases soil

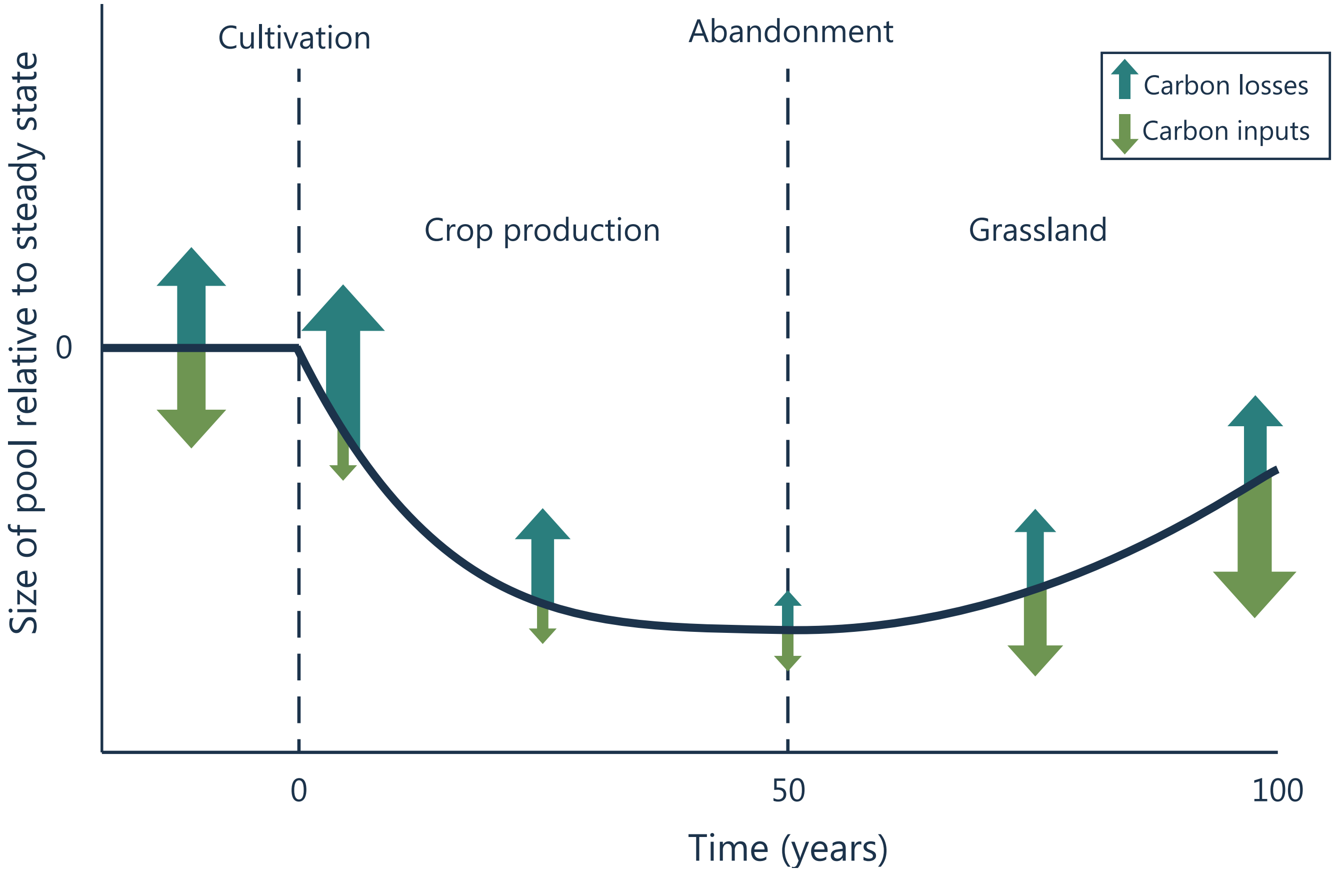

Figure 12. Impacts of cultivation and conversion to crop production and subsequent abandonment and succession to grassland vegetation on carbon inputs (green arrows), outputs (blue arrows), and soil carbon stocks (line) over time.

temperature and aeration, enhancing the activity of decomposers. Disturbance can greatly increase soil erosion as well, leading to deposition elsewhere on the landscape and additional losses of carbon as CO_2 to the atmosphere (Lal 1995; Lal et al. 1998).

Prescribed fire and grazing management are practices often utilized in grassland management and have important effects on species composition. Grassland ecosystems evolved with frequent fire and grazing, and their use is often important for maintaining the desired species composition and level of functioning in these systems. The implications of fire and grazing intensity on carbon stocks in grassland ecosystems, however, depends on many factors, highlighting the complex interactions between plant, soils, and climate that are important for carbon sequestration. For example, the exclusion of fire can lead to encroachment of woody shrubs in grasslands (Knapp et al. 2008). This change in species composition can reduce soil carbon pools in wetter grasslands; however, soil carbon stocks in more arid ecosystems may increase with encroachment (Jackson et al. 2002). Results from other studies have shown the opposite response, with woody encroachment from fire suppression in wetter grasslands increasing in soil carbon (Tilman et al. 2000), suggesting the importance of other factors such as soil textures. Likewise, grazing impacts on soil carbon can depend on interactions between soils, plant species, and climate. On sites with higher rainfall, grazing generally increases soil carbon on sandy, coarse-textured soils, while clay soils respond with weak increases to strong decreases in soil carbon. For arid grasslands, the opposite seems true: fine-textured clay soils show the largest increase in soil carbon to grazing relative to sandy soils (McSherry and Ritchie 2013). These patterns in response to proper grazing management suggest a general trend towards increases in soil carbon, which a global analysis estimates as an increase in carbon stocks averaging 2.9 percent (Conant et al. 2001). Greater water-holding capacity of clay soils may increase this benefit in arid systems (Steffens et al. 2008), while compaction of clay soils may restrict roots and actually reduce soil carbon over time in wet systems where soil moisture is not limiting (Sigua and Coleman 2010).

Management Practices for Grassland Carbon

Grassland carbon loss impacts many critical functions within ecosystems, such as reducing water-holding capacity, increasing the potential for wind and water erosion, and diminishing soil fertility. Best management practices for maintaining or restoring carbon in grasslands should, at a minimum, reduce soil disturbance to optimize these soil and water processes. Practices beneficial for carbon management include the reduction or cessation of tillage or minimizing the duration of bare soils by planting cover crops when cultivation is necessary (for example, when planting food plots for wildlife prior to seeding native species for restoration). Determining proper stocking rates for grazed lands in order to prevent overgrazing is critical for maintaining both desired species composition and adequate plant cover and biomass input to soils. Similarly, the use of prescribed fire can prevent woody or undesirable species from invading grasslands, and in some systems, reduces the litter layer to increase plant productivity (Briggs and Knapp 1995). Like stocking rates on grazed lands, the benefits of prescribed fire depend on the frequency of its use. Because nitrogen is lost from volatilization with fire, grasslands burned too frequently can show poor plant productivity and low tissue nitrogen levels, indicative of low soil nitrogen levels (Blair 1997). Grasslands impacted by a history of cultivation, overgrazing, fire suppression actions, or other disturbances to soils or plant communities can be restored through removal or careful management of the disturbance, and if plant cover or composition has been impacted severely, seeding of native species appropriate for the site.

Restoration of degraded grasslands by limiting soil disturbance, proper grazing management, thoughtful use of prescribed fire, or planting native species with deep root systems increases grassland carbon stocks by enhancing soil carbon inputs through plant productivity and limiting soil carbon losses. Seeding of grass or legume species into degraded grasslands can improve belowground production, and—in the case of legumes—improve soil fertility through nitrogen fixation. Fertilization and irrigation can have strong positive impacts to plant production and soil carbon stocks (Conant et al. 2001), although these practices are mostly applied in grasslands managed as pasture. Changes in ecosystem carbon from these management practices will vary, with the greatest gains expected to occur in cool humid climates and lowest in warm arid climates (Lal 2004). The recovery of soil carbon is typically a slow process, taking many decades to centuries, depending on the carbon balance of the system (fig. 12) (Burke et al. 1995). Despite these slow changes, the global potential for carbon sequestration from restoring degraded grasslands is significant, with the possibility to sequester approximately 3 Gt C per year—equivalent to reducing atmospheric CO_2 by 50 ppm over 50 years (Lal 2009). In addition to restoring degraded grasslands to improve carbon storage, grassland management strategies should recognize the critical goal of maintaining grassland cover and preventing degradation to conserve the ability of that land to continue sequestering carbon.

CARBON AS ONE OF MANY MANAGEMENT OBJECTIVES

Management objectives dictate the decisions land managers make. These objectives vary widely based on the landowner as well as the conditions of the ecosystem in question, and objectives may include any number of desired ecosystem benefits: water protection, wood production, wildlife, specific recreational opportunities, aesthetics, privacy, and more. Greenhouse gas mitigation is thus part of a wider array of management aims for forests and grasslands. Managers may choose to incorporate greenhouse gas mitigation as a management objective for a number of reasons, including increasing forest productivity or deriving benefits from participating in carbon markets. However, focusing solely on carbon could lead to non-optimal management decisions, and, in some situations, managing for carbon benefits may be at odds with other goals.

The tradeoffs inherent in balancing multiple management goals necessitate the recognition that it may not be possible to meet all goals, including those for carbon, in a single stand or at a single point in time (Ryan et al. 2010). Consideration of the effects of management actions on carbon require thinking broadly across large spatial scales and long timeframes to determine the true effects on atmospheric greenhouse gases (Harmon 2001). The following topics represent some examples of tradeoffs between carbon and other management goals or intentions; it is not meant to be an exhaustive list, but rather to illustrate some of the considerations that factor into carbon as one of many management objectives.

Wildlife and Carbon

The effects of wildlife management activities on carbon vary widely depending on the ecosystem and habitat characteristics of the location in question. For many habitats, management can provide carbon as a co-benefit in addition the many other forest uses and values, but in some cases people may decide to maintain lower carbon stocks as a side effect of pursuing other values, such as wildlife habitat. For example, forest restoration activities for the endangered red-cockaded woodpecker in the Southeast United States use thinning and prescribed burning to emulate frequent fire and maintain longleaf pine at low densities, which results in lower carbon densities (Martin et al. 2015). In the Cascade Mountains of Oregon, management activities to increase forest carbon storage are expected to benefit some wildlife species, such as the northern spotted owl and olive-sided flycatcher (Kline et al. 2016). Management to maintain high forest carbon levels, however, may not be as conducive with providing habitat for other species more dependent on early seral or less dense conditions like the pileated woodpecker and western bluebird.

Water and Carbon

The provisioning of water is another ecosystem service that, like carbon sequestration, is highly valued within forests and grasslands. Many organizations have land management objectives to protect water quality and maintain water quantity, including the timing and location of delivery (Brauman et al. 2007). Because water is an integral part of ecosystems, land management activities can affect, both positively and negatively, the hydrologic cycle; likewise, changes in the hydrologic cycle—such as those that are occurring as a result of climate change—will invariably affect ecosystem functions including carbon sequestration (Brauman et al. 2007, Furniss et al. 2010). For example, an analysis of multiple studies of afforestation activities showed substantial reductions in stream flow that lasted multiple decades due to increased water demands from plantation trees (Jackson et al. 2005). At the same time, afforestation practices can improve water quality by reducing erosion, mitigating peak flows, and increasing filtration and groundwater recharge, in addition to providing other important ecosystem benefits (Jackson et al. 2005). In natural (nonplantation) forests, there are many areas in which management can increase both carbon and water benefits. Harvesting woody residue as a source of renewable energy may provide greenhouse gas mitigation benefits by replacing fossil fuel emissions, but these activities may reduce the ability of the forest to regulate water quality and quantity or store carbon (Caputo et al. 2016). Lower intensity silvicultural practices may allow for wood harvest while also supporting water- and carbon-related ecosystem services (Caputo et al. 2016, Creedy and Wurzbacher 2001).

Risk Reduction

Observation indicates that risks to ecosystems and their associated human communities from undesired wildfire, insect and disease outbreaks, and invasive species (Kurz et al. 2008, Shifley and Moser 2016) are increasing, and that these can lead to carbon reductions (Amiro et al. 2010). Management actions can often focus on reducing such risks and creating more resilient and adapted systems. Management activities to reduce risk can affect the carbon cycle in numerous, often complex ways. For example, forest management is increasingly used to reduce risk of undesired wildfire by reducing fuel loads, while also meeting management objectives related to restoration of fire-adapted communities (Ager et al. 2010, Shinneman et al. 2012, Smith et al. 2016). There is some evidence, described above, to suggest that fuel-reduction treatments, which reduce forest carbon in the short term, may have long-term carbon benefits by increasing the growth of the residual stand and reducing risk of catastrophic fire (Boerner et al. 2008, Finkral and Evans 2008, McKinley et al.

2011). Fuel-reduction treatments may have the most substantial carbon benefit when harvest removals are relatively light, near-term fire occurrence is high, the treatments are effective, and thinnings provide wood for energy or products for long-term substitution (Millar et al. 2012).

Climate Change

Climate change is already having an impact on ecosystems across the world, and many of these changes are expected to continue or increase in the future (Melillo et al. 2014, Ryan and Vose 2012). Interest about mitigating atmospheric greenhouse gas emissions is driving concerns about managing carbon within ecosystems (Millar et al. 2012), and, as detailed in this chapter, forests and grasslands do play an important role in sequestering CO_2 and providing a source of renewable energy. At the same time, changes in the Earth's climate system are altering forests in dramatic ways, which can also have consequences for the emission of carbon and other greenhouse gases.

An intensification of the climate system is expected to lead to more extreme weather (IPCC 2012, Kunkel et al. 2012). Warmer temperatures and extreme weather have the potential to directly increase the frequency and severity of many types of disturbance, including drought, wildfire, and blowdown, as well as exacerbate pests, diseases, and other agents to further increase stress on ecosystems (Joyce et al. 2014, McKenzie et al. 2009, Ryan and Vose 2012). An example of the effect of climate on disturbance is seen in the Western United States, where climate variability drives wildfire occurrence in areas of high tree mortality from bark beetles (Hart et al. 2015, Mietkiewicz and Kulakowski 2016). Large disturbances are generally expected to increase, which could result in greater carbon releases from ecosystems (Millar and Stephenson 2015, Williams et al. 2016).

Even in the absence of severe disturbance, it is unclear whether many forests will be able to maintain their ability to sequester carbon at current rates. In many parts of the country, reforestation and the succession of young forest to older age classes has been a fundamental source of carbon uptake, and this sink may not be as strong in the future (Birdsey et al. 2006). Although warmer temperatures and enhanced CO_2 may maintain and even increase the growth of many forests over the next few decades (Arora et al. 2013), these benefits may be variable across the landscape and ultimately transitory (Oren et al. 2001). Boreal forests are especially vulnerable to climate change, and the decline of these systems leads to dramatic carbon emissions (Gauthier et al. 2015, Soja et al. 2007). Boreal and northern species within temperate systems also face potential declines as climate conditions become less suitable in the future and biomes shift toward ecosystems more tolerant of hotter and drier conditions that typically store less carbon (Bachelet et al. 2001, Duveneck et al. 2014, Lenihan et al. 2008). While new species may shift into these ecosystems, the pace of natural species migration is expected to be substantially slower than changes in climate (Iverson et al. 2004, Loarie et al. 2009).

It is increasingly important to consider the current and long-term effects from climate variability and change where land management seeks to maintain or increase carbon stocks or to provide a source of renewable energy. Adaptation actions, which work to reduce a system's vulnerability to a changing climate, can help to support beneficial carbon outcomes. Adaptation and mitigation are not alternatives to one another, but rather are part of an overall strategy to lessen the severity of the impacts of climate change (box 5). Management actions that serve to adapt forests and grassland ecosystems to changes in climate are critical for maintaining existing carbon pools and reducing losses of forest carbon to the atmosphere in the face of a changing climate.

BOX 5

Inter-Relationship Between Adaptation and Mitigation

Many approaches to adapt forests and grasslands to a future changing climate are complementary to mitigating rising atmospheric greenhouse gas levels. For example, increasing soil organic matter enhances soil carbon while also improving the water-holding capacity of soil and reducing the vulnerability of forests to more frequent intense drought. Additionally, actions that help adapt forests to future conditions help to maintain healthy, productive forests that continue to sequester carbon (Janowiak et al. 2014, Swanston et al. 2016). These actions include:

- Improving the ability of forests to resist pests and pathogens;
- Removing or preventing the establishment of invasive plant species;
- Protecting forests from severe fire and wind disturbance;
- Promoting diverse age classes with in stands; and
- Enhancing plant diversity, particularly of species or genotypes better adapted to future conditions.

Chapter 5: Forest Service Strategies and Organization

The U.S. Department of Agriculture (USDA), Forest Service's mission is "To sustain the health, diversity, and productivity of America's forests and grasslands for the benefit of present and future generations." The mission reflects the long history of the Forest Service as a leader in forest conservation and sustainable forest management, both nationally and internationally. A series of laws and regulations have contributed to this development, notably the Organic Administration Act of 1897 (16 U.S.C. 473-475, 477–482, 551), the Multiple Use Sustained Yield Act of 1960,[6] the Resources Planning Act of 1974,[7] and the National Forest Management Act of 1976.[8] A number of initiatives, as well as some policies described in this chapter, recognize that management of forest carbon is an important role of the Forest Service.

USDA STRATEGIC PLAN: FY 2014—2018

USDA's Strategic Plan for Fiscal Years 2014 through 2018[9] recognizes the benefits provided by national forests and private working lands. The strategic plan sets a goal of "ensuring our national forests and private working lands are conserved, restored, and made more resilient to climate change, while enhancing our water resources" (Goal 2). More specifically, the plan includes an objective that asks all USDA agencies to "lead efforts to mitigate and adapt to climate change, drought, and extreme weather in agriculture and forestry" (Objective 2.2).

FOREST SERVICE STRATEGIC FRAMEWORK FOR RESPONDING TO CLIMATE CHANGE

Developed in 2008, the "Forest Service Strategic Framework for Responding to Climate Change"[10] provided guidance for the agency to respond to climate change. The framework included seven strategic goals related to science, education, policy, alliances, adaptation, mitigation, and sustainable operations.

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[6] http://www.fs.fed.us/emc/nfma/includes/musya60.pdf

[7] http://www.fs.fed.us/emc/nfma/includes/range74.pdf

[8] http://www.fs.fed.us/emc/nfma/includes/NFMA1976.pdf

[9] http://www.usda.gov/documents/usda-strategic-plan-fy-2014-2018.pdf

[10] http://www.fs.fed.us/climatechange/documents/strategic-framework-climate-change-1-0.pdf

Specifically, the mitigation goal is related to forest carbon:

> *Mitigation: promote the management of forests and grasslands to reduce the buildup of greenhouse gases, while sustaining the multiple benefits and services of these ecosystems.*

The seven goals are all interconnected and are ultimately designed to achieve the same end: to ensure that Americans continue to get the ecosystem services they want and need from their forests and grasslands.

THE NATIONAL ROADMAP FOR RESPONDING TO CLIMATE CHANGE

In 2010, the Forest Service published the "National Roadmap for Responding to Climate Change."[11] The roadmap identifies the intended role of the Forest Service in responding to climate change by outlining short-term initiatives and longer term climate investments. The Forest Service responds to climate change through three modes of action: assess, engage, and manage. The agency recognized the need to manage for resilience through adaptation, mitigation, and sustainable consumption strategies. Furthermore, the roadmap clearly recognizes the role of forests:

> "Managing America's forests and grasslands to adapt to changing climates will help ensure that they continue to produce the benefits that Americans need while helping to mitigate the effects of a changing climate and to compensate for fossil fuel emissions through carbon storage in healthy forests."

To support the implementation of the roadmap by National Forest System (NFS) units, the Forest Service developed the Climate Change Performance Scorecard in 2011. The scorecard measures climate change progress by NFS units through 10 elements organized under 4 major dimensions—organizational capacity, engagement, adaptation, and mitigation.

The roadmap outlines a series of ongoing activities and immediate and longer term initiatives related to forest carbon. Ongoing activities and initiatives include a continuation of the role of the Forest Inventory and Analysis (FIA) program in providing official estimates of forest carbon stocks and flows for the United States, which are reported annually in the U.S. Greenhouse Gas Inventory[12] under the United Nations Framework Convention on Climate Change (UNFCCC).[13] The roadmap also expects continual development and application of tools to estimate carbon stocks and changes in those stocks.

The roadmap recognizes ongoing actions to "actively managing carbon stocks in forests, grasslands, and urban areas over time by doing the following:

- Rapidly reforesting land damaged by fires, hurricanes, and other disturbances, consistent with land management objectives.
- Conserving working forest and grasslands.
- Providing technical assistance for programs designed to enhance carbon sequestration potential through afforestation, reforestation, and practices that increase and maintain productivity and ecosystem health.
- Encouraging communities to retain green space and to plant and maintain trees.
- Using available tools to understand the impacts of management actions on carbon stocks and fluxes.

The roadmap summarizes the intended role of the Forest Service with respect to carbon as follows:

> Taking any tradeoffs into account, the Forest Service will work with partners to sustain or increase carbon sequestration and storage in forest and grassland ecosystems and to generate forest products that reduce and replace fossil fuel use. The Forest Service will

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[11] http://www.fs.fed.us/climatechange/pdf/roadmap.pdf

[12] https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-archive

[13] http://unfccc.int/essential_background/convention/items/6036.php

balance its mitigation goals against all other benefits that Americans get from healthy, resilient forests and grasslands, such as wildlife habitat, wood fiber, water quantity and quality, and opportunities for outdoor recreation.

USDA BUILDING BLOCKS FOR CLIMATE SMART AGRICULTURE AND FORESTRY

In late 2014, President Obama announced that by 2025 the United States intends to reduce greenhouse gas emissions by 26 to 28 percent below 2005 levels. Based on this direction, USDA revealed its focused approach for mitigation of greenhouse gas emissions in 2015. Known as the USDA Building Blocks for Climate Smart Agriculture and Forestry,[14] the plan was designed to help farmers, ranchers, forest landowners, and rural communities respond to climate change and to demonstrate the Department's commitment to reducing greenhouse gas emissions through the agriculture and forestry sectors. The 10 building blocks covered a range of technologies and practices to reduce greenhouse gas emissions, increase carbon storage, and generate clean renewable energy.

Four of the building blocks (Private Forest Growth and Retention, Stewardship of Federal Forests, Promotion of Wood Products, and Urban Forests) fall within the Forest Service's responsibilities. These building blocks are focused on maintaining or increasing the Nation's ability to sequester carbon through forest management, conserving and/or restoring the Nation's forests, reducing greenhouse gas emissions by storing carbon in wood products, and, simultaneously, offsetting emissions from conventional building materials.

The Forest Service, as part of USDA, has monitored the accomplishment of each of these four building blocks, including quantitative estimates of the CO_2 equivalent reductions that result from each building block. Annual reports on the progress of the building blocks are being prepared. A description of the building blocks and the progress to date can be found on the USDA Climate Solutions website.[15]

BRANCHES OF THE FOREST SERVICE

Within the policy framework described above, each major branch of the Forest Service considers carbon in the context of the branch's role in the agency. The NFS manages 193 million acres of the national forests and grasslands of the United States. State and Private Forestry (S&PF) provides assistance to States, local governments and private landowners in forest management. Research and Development (R&D) is the largest forest research organization in the world and develops science and technology related to forest and grassland management. In addition to these organizational deputy areas, International Programs (IP) supports the United States on global forest management issues and provides forest and grassland management assistance to other countries. A short summary of the principal policies affecting each of these branches follows.

National Forest System

Most of the laws, regulations, and formal policies that apply to the Forest Service relate to the management of the national forests and grasslands. The principal laws that govern the Forest Service (Organic Administration Act of 1897, Multiple Use Sustained Yield Act of 1960, Resources Planning Act of 1974, and National Forest Management Act of 1976) pertain primarily to the management of these lands.

Management of national forests and grasslands is also governed by a variety of other laws and regulations including the Threatened and Endangered Species Act,[16] the National Environmental Policy Act (NEPA),[17] and many others that directly influence the management of these resources. A number of laws and regulations have established a set of designated areas—including wilderness, wild and scenic rivers, national monuments, and roadless areas—where timber harvest and road construction are

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[14] https://www.usda.gov/oce/climate_change/buildingblocks.html

[15] http://www.usda.gov/documents/building-blocks-implementation-plan-progress-report.pdf

[16] https://www.fws.gov/endangered/esa-library/pdf/ESAall.pdf

[17] https://ceq.doe.gov/laws-regulations/laws.html

prohibited or severely restricted. These areas comprise more than 103 million acres, or more than half of the 193-million-acre NFS. Land management plans further direct how forest resources are to be managed consistent with applicable laws and regulations. The following summarizes the main laws, regulations, and programs that provide support for including carbon outcomes in land management.

Climate Change Performance Scorecard

To implement the "National Roadmap for Responding to Climate Change" throughout the NFS, the Forest Service adopted the Climate Change Scorecard.[18] The scorecard requires responses on an annual basis from each NFS region and unit against a set of criteria designed to measure progress on the 10 elements. Element 9 is focused on carbon assessment and stewardship. For complete success on this element, an NFS unit needs to be able to respond positively to three questions:

1. Does the unit have a baseline assessment of carbon stocks?
2. Does the unit have an assessment of the influence of disturbance and management activities on these stocks?
3. Is the unit integrating carbon stewardship with the management of other benefits being provided by the unit?

In the initial years of the scorecard, most of the individual units could not affirmatively respond to all three questions. Therefore, the Forest Service developed methods and produced baseline assessments of forest carbon stocks and the influence of disturbances and management activities for each NFS unit. The Forest Service Climate Change Advisor's Office (now Office of Sustainability and Climate) published the baseline forest carbon assessments in 2015. These assessments allowed NFS units to make progress on question 1 of Element 9. Since 2015, the Forest Service developed new methods for evaluating the influence of management and disturbances on those stocks, and each NFS unit is applying the methods (Raymond et al. 2015; Zhang et al. 2015; Healey et al., in press; Healey et al. 2014; Zhang et al. 2012; Chen et al. 2000a; Chen et al. 2000b). These regional assessments expand upon previous assessments of baseline carbon stocks across individual national forests and, at the regional scale, by assessing how stocks at those scales are affected by timber harvesting, natural disturbances, land-use change, climate variability, increasing atmospheric carbon dioxide concentration, and nitrogen deposition.

Individual national forests and grasslands have been able to use this information to more carefully consider influences on carbon stocks as part of project planning in their land management activities, as well as make progress on question 2 of Element 9. In 2016, approximately 90 percent of NFS units were able to respond affirmatively to this element.

Planning Rule and Planning Handbook

The 2012 Planning Rule (36 CFR [Code of Federal Regulations] 219) formally clarified the role of national forests and grasslands in providing ecosystem services, which include, among many things, long-term carbon storage (36 CFR 219.19). In the context of assessments for land management planning, the responsible Forest Service official identifies and evaluates existing information relevant to numerous characteristics of the resource, including providing a baseline assessment of carbon stocks.

The 2012 planning rule was promulgated to implement the National Forest Management Act requirement for land management plans that guide the sustainable management of national forests and grasslands. The planning rule describes a commitment to protect and restore national forests and grasslands for the benefit of communities, natural resources, and the environment. Management activities on NFS units are required to be consistent with these land management plans.

The 2012 planning rule, the Planning Forest Service Manual (FSM 1920),[19] and the Land Management Planning Forest Service Handbook (FSH 1909.12)[20] are the formal regulations and policies that describe how the planning is to be done and the content of those plans. The planning rule explicitly requires that the

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[18] http://www.fs.fed.us/climatechange/advisor/scorecard.html

[19] http://www.fs.fed.us/cgi-bin/Directives/get_dirs/fsm?1900

[20] http://www.fs.fed.us/cgi-bin/Directives/get_dirs/fsh?1909.12

assessments done for every plan revision must identify and evaluate information about a baseline assessment of carbon stocks and benefits people obtain from the NFS planning area (ecosystem services) (36 CFR 219.6 (b)(4&7)). Every revised plan must provide for ecosystem services (36 CFR 219.10), with long-term carbon storage (36 CFR 219.19) being recognized as an ecosystem service.

FSH 1909.12 describes in more detail the expected assessment of carbon stocks and ecosystem services in chapter 10 and content of plans in chapter 20.

For the assessment, the handbook (FSH 1909.12, chapter 10, section 12.4) clarifies that the responsible official for the plan revision shall identify and assess available information relevant to the plan area for a baseline assessment of carbon stocks on the land and in harvested wood products. The assessment is developed to understand the role of the plan area in sequestering carbon, historic and future influences of disturbances and activities on carbon stocks, and how carbon storage may be changing and might be influenced by management. This section of the handbook further describes resources, tools, and other information that may be useful in assessing carbon stocks and the influences on those stocks.

FSH 1909.12 (chapter 10, section 13.12) also directs that each plan revision should identify and evaluate key ecosystem services, which, depending on the nature of the plan area, could include carbon stocks or carbon sequestration. Assuming carbon is one of these key ecosystem services, an interdisciplinary team should identify and evaluate available information about the scale of the plan area's carbon contribution, the conditions and trends of the plan area's carbon, the stressors likely to affect carbon, the conditions and trends of the ecosystem needed to maintain the plan area's carbon, the influence of lands outside the plan area on carbon, and the relationship of carbon to social, cultural, and economic conditions.

FFSH 1909.12 (chapter 20, section 23.21b) describes how the plan should integrate the key ecosystem services identified in the assessment in the land management plan. Assuming carbon is one of these key ecosystem services, the plan should describe the desired conditions for carbon in the plan area that may vary by management or geographic area. In developing plan objectives, the interdisciplinary team should consider the linkage between carbon and how plan objectives would contribute to carbon storage or sequestration. Standards and guidelines may also be needed to achieve desired outcomes for carbon.

The plan monitoring program or broad-scale monitoring program may also include questions and indicators related to carbon stocks or carbon sequestration.

National Environmental Policy Act

NEPA requires Federal agencies to evaluate the potential environmental effects of their proposed actions. In January 2009, the Forest Service issued guidance on considering climate change, including consideration of carbon stocks, in project-level planning as part of the NEPA process.[21] This guidance outlines these basic concepts:

1. Climate change effects include the effects of agency action on global climate change and the effects of climate change on a proposed project.
2. The agency may propose projects to increase the adaptive capacity of ecosystems it manages, mitigate climate change effects on those ecosystems, or to sequester carbon.
3. Some project proposals may present choices based on quantifiable differences in carbon storage and greenhouse gas emissions between alternatives.

Carbon effects need to be considered in proportion to the nature and scope of the action in question. Not all projects will have a cause-effect relationship with carbon stocks or carbon sequestration. The guidance indicates that for some projects, quantifying greenhouse gas emissions or carbon sequestration effects may help to inform the decision based on tradeoffs among different alternatives. The guidance references various tools that can be used for estimating these effects.

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[21] http://www.fs.fed.us/emc/nepa/climate_change/index.htm

Healthy Forests Restoration Act

The Healthy Forests Restoration Act of 2003 (16 U.S.C. 6501)[22] directs the Secretary of Agriculture, with respect to NFS lands, to plan and conduct hazardous fuel-reduction projects (fuel projects) on specified types of Federal lands. The act directs the Secretary to fully maintain, or contribute toward the restoration of, the structure and composition of old-growth stands according to the pre-fire-suppression, old-growth conditions characteristic of the forest type.

Carbon sequestration is listed in the stated purposes of the Healthy Forest Restoration Act:

"**(6)** to protect, restore, and enhance forest ecosystem components—

> **(A)** to promote the recovery of threatened and endangered species;
> **(B)** to improve biological diversity; and
> **(C)** to enhance productivity and carbon sequestration."

Ecosystem Restoration Directive

The Forest Service published an ecosystem restoration directive in April 2016 as part of FSM 2020.[23] This addition provides policy for reestablishing and retaining the ecological resilience of NFS lands and resources to achieve sustainable multiple-use management and provide a broad range of ecosystem services. The stated objective of the directive is "Ecosystems ecologically or functionally restored, so that over the long term they are resilient and can be managed for multiple use and provide ecosystem services, including but not limited to carbon storage and sequestration" (FSM 2020.2).

The directive also provides that in the development of goals or objectives for ecosystem restoration, the Forest Service should consider "the recovery, maintenance, and enhancement of carbon stocks" (FSM 2020.3 (2)(d)). Both the policy and the preamble to the policy make clear that carbon is one of many ecosystem services provided by forests and that carbon is one, but not the only, consideration in proposing restoration activities.

Pilot Carbon Sequestration Projects with National Forest Foundation

In July 2007, the Forest Service and the National Forest Foundation (NFF) entered into a Memorandum of Understanding and Collection Agreement to develop demonstration projects supported by the NFF's Carbon Capital Fund.[24] The agreement, which was renewed in 2012, provides opportunities for individuals and organizations to invest in carbon offset reforestation projects and provides the Forest Service an opportunity to demonstrate how forest management may be used to mitigate greenhouse gas emissions.

Donations to the Carbon Capital Fund are used to replant areas on national forests that have been so severely altered by wildfire that these formerly forested areas cannot regenerate naturally. The reforestation demonstration projects are projected to sequester a measurable and verifiable amount of carbon beyond what would occur without the planting. Funding from the NFF covers the Forest Service's expenses for these projects and estimates a carbon benefit based on the amount of carbon that the project will generate as compared to the amount of carbon that would occur without the project.

The project agreements do not create any legal rights to carbon credits, offsets, or any other types of claims related to carbon. FSH 1509.11, Chapter 90, Sec. 91.2, Exhibit 01 Provision H.12 has directives established limiting provisions to include in these agreements as follows:

> Any and all activities entered into or approved by this agreement will create and support afforestation/reforestation efforts within the National Forest System without generating carbon credits. The Forest Service does not make claims of permanence or any guarantees

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[22] http://uscode.house.gov/view.xhtml?req=granuleid:USC-prelim-title16-section6501&num=0&edition=prelim

[23] https://www.gpo.gov/fdsys/pkg/FR-2016-04-27/pdf/2016-09750.pdf

[24] http://www.fs.fed.us/ecosystemservices/Carbon_Capital_Fund/index.shtml

of carbon sequestration on lands reforested or afforested through partner assistance. The Forest Service will provide for long-term management of reforested and afforested lands, according to applicable Federal statute, regulations, and forest plans.[25]

State and Private Forestry

The S&PF Branch of the Forest Service actively engages in a variety of programs associated with forest conservation, management, and utilization. Conservation of forests retains existing forest carbon stocks and maintains the ability of forests to continue to sequester carbon—two functions of forests that could be lost if the forest land is converted to other uses. S&PF provides technical and financial assistance to landowners and resource managers to help sustain the Nation's forests and protect communities and the environment from wildland fires. Three themes guide the work of S&PF: conserve working forest landscapes, protect forests from harm, and enhance public benefits from trees and forests. A brief summary of these programs follows.

Forest Legacy Program

The Forest Legacy Program[26] identifies and protects environmentally important forest land threatened by conversion to nonforest use by acquiring conservation easements or fee interest in lands. Projects are evaluated for their importance (which includes economic and environmental criteria), threat of conversion, and strategic contribution of the proposed acquisition to the landscape. Forest land that is conserved is protected in perpetuity. Landowners who participate take on the long-term responsibility to manage the land in a manner consistent with the terms specified in the conservation easement and according to a multiresource management plan that addresses a suite of natural-resource elements (soil and water, biological diversity, recreation, timber, and threatened and endangered species) where present. The program requires annual monitoring of conservation easements to ensure that the specified conservation values are maintained through time.

Community Forest Program

The Community Forest Program[27] aims to secure a variety of community benefits through grants to local governments, tribal governments, and qualified nonprofit organizations to acquire community forests through fee acquisition. By creating community forests, communities and tribes are able to provide public access and recreational opportunities, protect vital water supplies and wildlife habitat, sequester carbon, provide demonstration sites for private forest landowners, and derive financial and community benefits from sustainable management. These forests are managed according to a community forest plan that guides the long-term management and associated community benefits of the community forest.

Forest Stewardship Program

The Forest Stewardship Program (FSP)[28] promotes active forest management by willing family forest owners to produce healthy, resilient forest landscapes. Assistance offered through the Forest Stewardship Program also provides landowners with enhanced access to other USDA conservation programs, forest certification programs, and forest products. Managed forest lands maintain forests and have an important role in the sequestration of carbon.

Urban and Community Forestry

Urban and Community Forestry (UCF)[29] is a cooperative program of the Forest Service that focuses on the stewardship of urban natural resources. Urban forests are dynamic ecosystems that provide needed environmental services by cleaning air and water, helping to control stormwater, conserving energy, and sequestering carbon. UCF provides technical, financial, research, and educational services to local governments, nonprofit organizations, community groups, educational institutions, and tribal governments. UCF includes a

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[25] http://www.fs.fed.us/cgi-bin/Directives/get_dirs/fsh?1509.11

[26] http://www.fs.fed.us/spf/coop/programs/loa/flp.shtml

[27] http://www.fs.fed.us/spf/coop/programs/loa/cfp.shtml

[28] http://www.fs.fed.us/spf/coop/programs/loa/fsp.shtml

[29] http://www.fs.fed.us/ucf/

variety of tools related to carbon in urban forests. The program is delivered through its legislative partners: the State forestry agencies in 59 States and U.S. territories.

Wood Innovations

The Wood Innovations[30] supports traditional wood utilization projects, expands wood energy markets, and promotes using wood as a construction material in commercial buildings. The Forest Service supports proposals that significantly stimulate or expand wood energy and wood products markets that support the long-term management of NFS and other forest lands. Wood is a versatile, durable, abundant, and cost-effective renewable resource that provides numerous environmental benefits, including storing carbon and substituting for fossil-fuel-intensive materials when used in construction and offsetting the release of fossil carbon when used for energy production.

Research and Development

Forest Service R&D has a long history of scientific investigation focused on carbon and nutrient cycling in forest ecosystems and has developed various tools and accounting procedures for estimating carbon stocks in forest and wood products pools. Through ongoing research, the accuracy of these estimates is constantly improving. The resulting data constitutes the foundation for U.S. forest carbon reporting in response to national and international commitments.

A 1990 amendment to the Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974 required that subsequent RPA assessments include an analysis of the potential effects of global climate change on the condition of renewable resources on the forests and rangelands of the United States. The 2010 RPA report and supporting documents include extensive consideration of forest carbon stock changes, the relationship of wood and bioenergy markets to land-use change, and evaluation of how various climate, demographic, and economic scenarios may impact U.S. forest carbon stocks.

The R&D FIA program, described earlier, provides data and estimates of forest carbon that support forest carbon analysis at various scales. This includes national reporting of greenhouse gas inventories under the UNFCCC analysis for the Montreal Process criteria and indicators for sustainable forest management, and greenhouse gas registries for States and regions. FIA data are also the basis for the forest carbon projections in the RPA assessments, which are a key input to U.S. reporting obligations under the UNFCCC Climate Action Report every 4 years and a Biennial Report every 2 years. Both documents include projections of greenhouse gas emissions and removals from the forestry sector.

International Programs

Internationally, the Forest Service supports the Global Climate Change Initiative and efforts to reduce emissions from deforestation and forest degradation and to enhance carbon stocks through sustainable forestry, forest landscape restoration, and support of programs in developing countries. This "sustainable landscapes" strategy is broader than forests and seeks to develop new low-emissions development approaches where forest protection, sustainable agricultural production, and economic growth move forward together.

The Forest Service works closely with partners in more than 20 countries in Latin America, Africa, and Asia to provide technical assistance, training, and research related to reducing deforestation and forest degradation and to support developing countries' national Reducing Emissions from Deforestation and Forest Degradation (REDD+)[31] programs. This assistance includes facilitating development of forest carbon inventories, conservation of wetland forests, improving sustainable forest management, and developing and disseminating technologies and systems to detect and combat illegal logging—a significant source of carbon loss through deforestation and forest degradation.

SilvaCarbon[32] is a technical-cooperation program that supports the Global Climate Change Initiative and is closely coordinated with international organizations

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[30] http://www.fs.fed.us/science-technology/energy-forest-products/wood-innovation

[31] http://www.un-redd.org/

[32] http://www.silvacarbon.org/

and other Federal agencies, including the U.S. Agency for International Development, U.S. Geological Survey, U.S. Environmental Protection Agency, U.S. Department of State, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, and Smithsonian Institution. The program addresses technical issues such as sampling design, data capture, collection and analysis, and estimation of carbon stocks and flows.

The Forest Service works closely with the U.S. Department of State and other government agencies to support the work of the UNFCCC. The Forest Service is a founding member of Megaflorastais, a network of forest agency leaders from the 12 largest forested countries, who meet to discuss global issues related to forest governance and climate change. The Forest Service also works directly with partners in countries around the world to enhance sustainable forestry.

Summary: Considering Carbon in Land Management

Although carbon is a relatively new consideration in land management, it is consistent with sustaining the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations. Land management actions on public and private forests and grasslands can be designed to achieve carbon outcomes while meeting other sustainable resource management objectives. Forests are important in capturing and storing carbon, both onsite and in products, and management of these lands can contribute to mitigating climate change. The following considerations should be at the forefront when considering carbon along with other management objectives:

1. **Emphasize ecosystem function and resilience** (Function First). Carbon sequestration capacity depends on sustaining and enhancing ecosystem function. Long-term sequestration should be planned in the context of changing climate and other environmental drivers. Management actions that help maintain resilient forests or transition vulnerable forests to a fully functioning and resilient state are more likely to store sequestered carbon over the long run.
2. **Recognize carbon sequestration as one of many ecosystem services** (One of Many Services). Carbon sequestration is one of many ecosystem services provided by forests and grasslands. Strategies for including carbon in forest and grassland management must consider the suite of resources and outcomes desired from management actions. A balanced and comprehensive program of sustainable management will consider many ecosystem services, including carbon sequestered in biomass, soils, and wood products.
3. **Support diversity of approach** (Diverse Approaches). Decisions about carbon in America's forests are influenced by ownership goals, policy, ecology, geography, socioeconomic concerns, and other factors that vary widely. The Forest Service supports a variety of approaches to managing carbon and deriving value from carbon that are compatible with the objectives of different owners. A wide diversity in approaches can also foster rapid learning about forest, grassland, and carbon management in the context of climate adaptation.
4. **Consider system dynamics and scale in decision making** (Scale and Timeframe). Different ecosystems sequester carbon in different ways, at different rates, and within differing mosaics of landscape plans and

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trends. The carbon effects of forest and grassland management options should be evaluated within the carbon dynamics of long timeframes and landscape scales, with explicit consideration of uncertainties and assumptions. Where practical, system dynamics should be broadened beyond the ecosystem to consider full life-cycle impacts of decisions, including carbon storage in forest products and substituting wood-based options for fossil-fuel-intensive applications.

5. **Use the best information and analysis methods** (Decision Quality). Forest management and policy decisions should be based on the best available science-based knowledge and information about system response and carbon cycling in forests, grasslands, and wood products. This information should be used wisely by dealing directly with uncertainties, risks, opportunities, and tradeoffs through sound and transparent risk-management practices. Forest plan revision, project-level implementation, and other decision processes should consider tools and approaches that explicitly address uncertainty, risks, and opportunities about climate impacts and forest carbon response.

Including carbon in land management planning activities through these considerations supports the widespread approaches of ecosystem and watershed management and does not require significant alteration of management strategies and approaches. A balanced approach to including carbon in management activities may, however, complement existing objectives and priorities even as it helps mitigate the Nation's greenhouse gas emissions and promote climate adaptation.

Glossary

autotrophic respiration: The metabolism of organic matter by plants.

biomass: The mass of living organic matter (plant and animal) in an ecosystem. Biomass also refers to organic matter (living and dead) available on a renewable basis for use as a fuel. Biomass includes trees and plants (both terrestrial and aquatic), agricultural crops and wastes, wood and wood wastes, forest and mill residues, animal wastes, livestock operation residues, and some municipal and industrial wastes.

carbon sequestration: The process of increasing the carbon content of a carbon reservoir other than the atmosphere; often used narrowly to refer to increasing the carbon content of carbon pools in the biosphere and distinguished from physical or chemical collection of carbon followed by injection into geologic reservoirs, which is generally referred to as "carbon capture and storage."

carbon cycle: The term used to describe the flow of carbon (in various forms such as carbon dioxide [CO_2], organic matter, and carbonates) through the atmosphere, ocean, terrestrial biosphere, and lithosphere.

carbon equivalent: The amount of carbon in the form of carbon dioxide (CO_2) that would produce the same effect on the radiative balance of the Earth's climate system.

carbon stock change: The change in carbon stocks over time, calculated by taking the difference between successive inventories and dividing by the number of years between these inventories for each national forest. A positive change means carbon is being removed from the atmosphere and sequestered by the forests (i.e., carbon sink) while a negative change means carbon is added to the atmosphere by forest-related emissions (i.e., carbon source).

CO_2 equivalent: The amount of carbon dioxide (CO_2) that would produce the same effect on the radiative balance of the Earth's climate system as another greenhouse gas, such as methane (CH_4).

CO_2 fertilization: The phenomenon in which plant growth increases (and agricultural crop yields increase) due to the increased rates of photosynthesis of plant species in response to elevated concentrations of carbon dioxide (CO_2) in the atmosphere.

ecosystem respiration: The total respiration of all organisms living in a given ecosystem.

flux: The transfer of carbon from one carbon pool to another.

global warming potential: A factor describing the radiative forcing impact (e.g., warming of the atmosphere) of one unit mass of a given greenhouse gas relative to the warming caused by a similar mass of carbon dioxide (CO_2); methane (CH_4), for example, has a global warming potential of 23.

greenhouse gas: Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds. This property causes the greenhouse effect. Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere.

gross primary production: The sum of total canopy photosynthesis for a unit of area over a given unit of time.

harvested wood products: Includes all wood material (including bark) that leaves harvest sites. Slash and other material left at harvest sites should be regarded as dead organic matter.

heterotrophic respiration: The metabolism of organic matter by bacteria, fungi, and animals.

leakage: The situation in which a carbon sequestration activity (e.g., tree planting) on one piece of land inadvertently, directly or indirectly, triggers an activity that in whole or part counteracts the carbon effects of the initial activity.

mitigation: A human intervention to reduce the sources of or to enhance the sinks of greenhouse gases.

net ecosystem exchange: The net flux of carbon between the land and the atmosphere, typically measured using eddy covariance techniques. Net ecosystem exchange and net ecosystem production are equivalent terms but are not always identical because of measurement and scaling issues, and the sign conventions are reversed; positive values of net ecosystem exchange usually refer to carbon released to the atmosphere (i.e., a source), and negative values refer to carbon uptake (i.e., a sink).

net ecosystem production: The net carbon accumulation within the ecosystem after all gains and losses are accounted for, typically measured using ground-based techniques. By convention, positive values of net ecosystem production represent accumulations of carbon by the ecosystem, and negative values represent carbon loss.

net primary production: The net uptake of carbon by plants in excess of respiratory loss.

pool/reservoir: Any natural region or zone, or any artificial holding area, containing an accumulation of carbon or carbon-bearing compounds or having the potential to accumulate such substances.

sequestration: The long-term storage of carbon in plants, soils, geologic formations, and the ocean, occurring both naturally and as a result of anthropogenic activities.

sink: In general, any process, activity, or mechanism that removes a greenhouse gas or a precursor of a greenhouse gas or aerosol from the atmosphere; in this report, a sink is any regime or pool in which the amount of carbon is increasing (i.e., is being accumulated or stored).

source: In general, any process, activity, or mechanism that releases a greenhouse gas or a precursor of a greenhouse gas or aerosol into the atmosphere; in this report, a source is any regime or pool in which the amount of carbon is decreasing (i.e., is being released or emitted).

stocks: The amount or quantity contained in the inventory of a pool or reservoir.

woody biomass: The byproduct of management, restoration, and hazardous fuel-reduction treatments, as well as the product of natural disasters, including trees and woody plants (limbs, tops, needles, leaves, and other woody parts, grown in a forest, woodland, or rangeland environment).

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Units

Metric ton (Mt) = 1,000 kilograms = Megagram (Mg)
Million metric tons (MMt) = 10^9 kilograms = Teragram (Tg)
Gigaton (Gt) = 10^{12} kilograms = Petagram (Pg)

1 kilogram carbon (C) = 3.664 kilograms carbon dioxide (CO_2)

Unit Conversion Factors

When you know:	**[*]Multiply by:**	**To find:**
Centimeters (cm)	0.394	Inches (in)
Meters (m)	3.28	Feet (ft)
Hectares (ha)	2.47	Acres (ac)
Kilograms (kg)	2.20462	Pounds (lbs)
Metric tons (Mt)	1.10	U.S. tons (T)
Square meters (square m)	10.76	Square feet (square ft)
Kilograms per cubic meter (kg per cubic m)	0.0624	Pounds per cubic foot (lbs per cubic ft)
Metric tons per hectare (Mt per ha)	0.446	U.S. tons per acre (T per ac)
Square meters per hectare (square m per ha)	4.37	Square feet per acre (square ft per ac)
Kilograms per square meter (kg per square m)	0.2048	Pounds per square foot (lbs per square ft)
Kilogram per hectare (kg per ha)	0.892	Pounds per acre (lbs per ac)

[*] Divide one by the multiplication factor to reverse the conversion.