TECHNICAL MEMORANDUM

CLIMATE PROJECT: Carbon Sequestration and Storage by California Forests and Forest Products

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on behalf of California Forests for The Next Century

FORESTS For The Next Century

TECHNICAL MEMORANDUM CH2MHILL

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The forest sector's carbon cycle is structured about four major carbon pools—the forest, forest products-in-use, products disposed in landfills, and fossil fuel displaced by forest products and bioenergy in end-use markets.

When only the standing forest is considered, rates of growth, respiration, and decay control the amount of carbon removed by forests from the atmosphere. Compared to intensively managed forests, unmanaged or less intensively managed forests may remove greater amounts of atmospheric carbon over limited timeframes during forest development due to inefficiencies of converting from one type of forest structure to another. Eventually, the limited advantage of less managed forest dwindles because deferred tree harvesting causes forest respiration to approach growth (i.e., no net carbon removal), or causes the forest to succumb to wildfire or some other catastrophe because fuel and forest mortality hazards accumulate.

Actively managed forest stands in California remove and store significantly greater amounts of carbon than unmanaged stands or stands under longer harvest cycles in the same area when both the standing forest and captured forest products are taken into account. Carbon stored in forest products during and after their useful life ensures a substantial degree of permanence in the carbon storage equation and dampens flow back to the atmosphere. The advantage is most pronounced after considering the marketplace substitution of wood products for fossil fuel and more energy-intensive product alternatives. When product substitution is considered, forestry can lead to a significant reduction in atmospheric carbon by generating bioenergy and displacing fossil fuel-intensive products.

In any carbon accounting scheme, recognizing only the carbon stored in forests incorrectly subsidizes the no-harvest and extensive forest management scenarios and diminishes the value of actively managed forests for reducing greenhouse gases. Incentives for more intensive forest management probably would increase the carbon stored in the four major carbon pools. This, in turn, would reduce the risk of catastrophic carbon losses to the atmosphere from accumulating fire, insect, and disease hazards while keeping California's forestland in forest use.

Introduction

This technical memorandum portrays the carbon cycle of California forests and forest products. It describes, by stocks and flows, the carbon sequestration benefits of California forests and forest products, and compares potential carbon sequestration under active and passive forest management. (Active forest management typifies private industrial forestland and passive forest management characterizes national forests.) This paper explains how active forest management accelerates carbon sequestration and contributes to storage, and how this knowledge can improve the accuracy of carbon inventories and accounting.

Forest management's role in carbon cycling is often viewed as one of expanding the terrestrial pool in forested ecosystems. Occasionally, we forget that the removal of wood and fiber for storage in product form or use as bioenergy also leads to reductions in atmospheric concentrations of carbon dioxide. Therefore, this review recognizes that the forest sector's carbon equation does not end in the woods; it describes the carbon cycle from stump to forest product, product recycling and reuse, and eventual decay. Tree harvesting results in few immediate carbon emissions and, unlike passive forest management, yields carbon-storing products of surprising endurance. Opportunities to displace fossil fuel consumption by utilizing bioenergy and by substituting forest products for energy consuming materials further enhance the forest sector's appeal for managing greenhouse gases. With full knowledge of the role played by California forests and forest products, a more comprehensive, fair, and fact-based forest sector protocol for documenting carbon sequestration and storage can be developed for use in California.

The following section on the forest Carbon Cycle gives the context for appreciating elements of carbon ecology, and its stocks and flows. Generally, the section focuses on carbon management concepts with policy implications. Although qualitative in its descriptions, it contains references to source materials for readers seeking a deeper level of understanding.

The subsequent section, entitled Quantifying Carbon Stocks and Flows, provides suggestions for information resources, factors, equations, and quantitative relationships that describe the regulation of stocks and flows in the carbon cycle. The section attempts to simplify the relationships within the carbon cycle, to varying degrees, so that we can create a more accurate picture of management consequences and potential for reducing California's in-state carbon emissions.

The Carbon Cycle

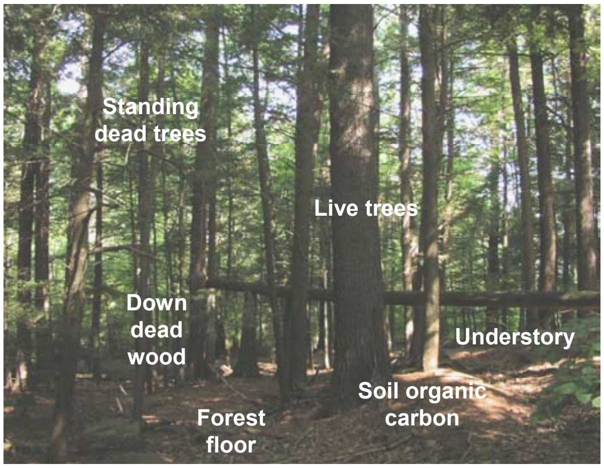


Figure 1. Carbon in the forest (after Birdsey and Friend 2005)

Most school children are taught about the role of forests in the carbon cycle: absorption by live trees and understory, and storage in vegetation and soil (Figure 1). In the absence of fire or other disturbances, carbon accumulates above and below the ground.

The complete story includes the influence of sustainable forestry practices on the rate of carbon absorption by trees, the efficiency of wood utilization, the conservation of fossil fuels, and the measures to prevent massive releases of carbon by insects, disease, and wildfire (see Figure 2, from The Forest Foundation). Manufactured wood products prolong carbon storage while working forests continue to absorb more carbon. Wood waste is captured for power generation, which reduces the drain on non-renewable fossil fuels.

The cycle of carbon in forests and forest products is a system of carbon stocks (pools) and flows of carbon among them. In our human environment, there are many possible carbon storage pools for wood products-in-use, as there are numerous pools in the forest. Carbon flows from pool to pool when changes occur in the amount of carbon stored in forest elements or forest product categories.

Heath and Birdsey (2000) diagrammed the major carbon stocks and flows of California forests and forest products (Figure 3). The right side of their flowchart describes forest carbon. The blue highlighted area (left side) shows the fate of carbon removed by harvest, including storage in forest products and landfills, and biomass for energy generation. Note that carbon imports and exports are set off in a side box because their contributions are too complicated to show in a simple diagram. (Comprehensive carbon accounting tracks wood grown in California forests even if it is exported, processed in other countries, and then imported.) Also, not shown in their diagram, but acknowledged, is the amount of carbon used for energy consumption as carbon flows from pool to pool.

For convenience, the carbon cycle discussion in this paper is structured around the four major carbon pools of the forest sector—the forest, forest products-in-use, products disposed in landfills, and fossil fuel displaced by forest products and bioenergy in end-use markets.

California Forests

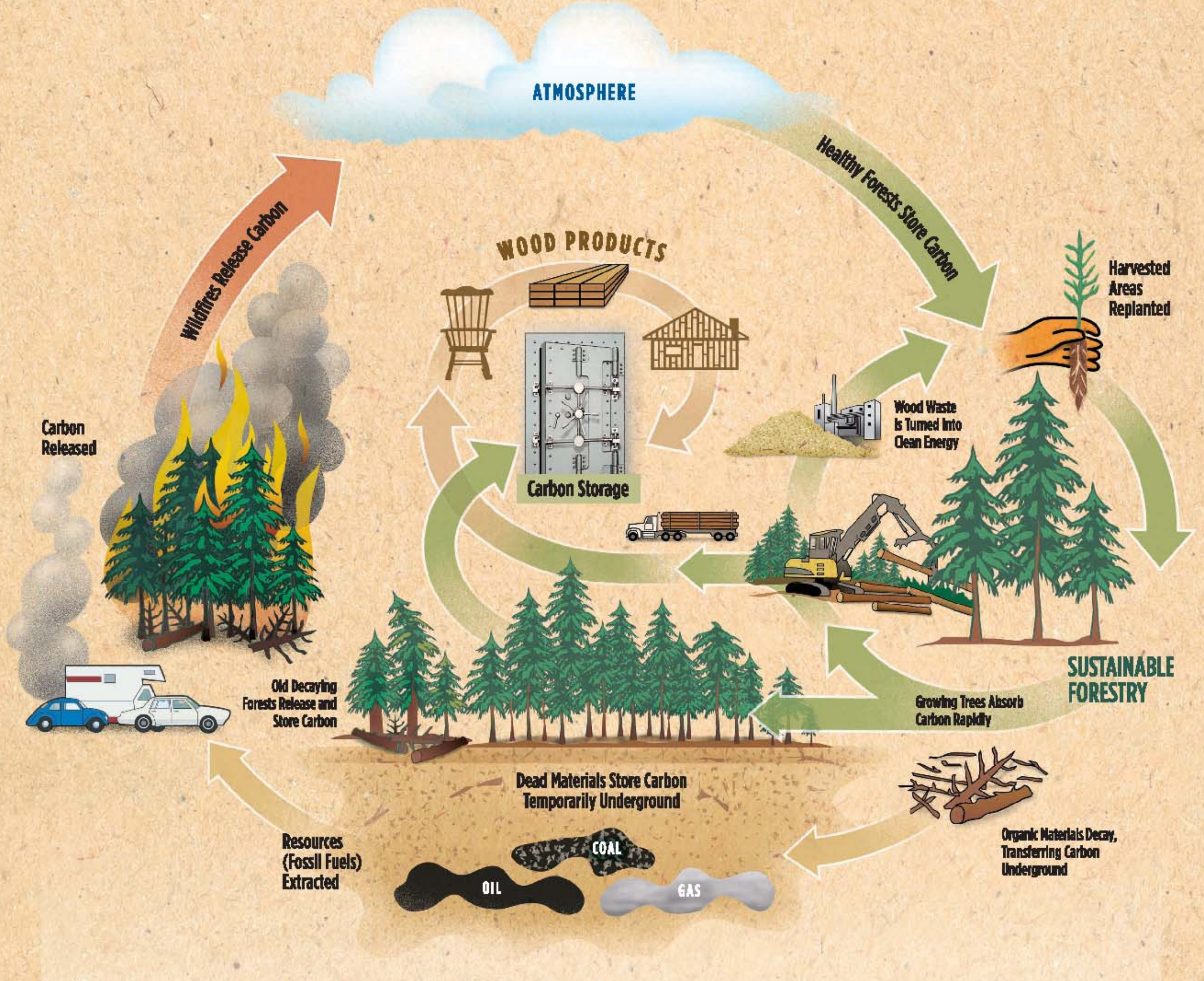
California supports over 33 million acres of forestland, of which about 23,550,000 acres are productive (i.e., produces in excess of 20 cubic feet per acre per year of wood) (Christensen et al. 2007). Of the productive forestland, about 19,551,000 acres are classified as timberland; that is, as productive land not legally restricted from harvest.

Most of the productive forestland is covered by softwood forest—mainly the California mixed conifer, ponderosa pine, fir/spruce/mountain hemlock, redwood and Douglas-fir groups (Christensen et al. 2007). Productive hardwood forests are mostly the western oak and tanoak/laurel groups.

Figure 2.

The Carbon Cycle

FORESTRY NEVER LOOKED SO COOL



Carbon Released

Catastrophic fires release carbon that has been stored in trees into the atmosphere. Manufacturing and automobiles also contribute carbon to the atmosphere by burning fossil fuels. Natural processes like volcanoes and decomposition also release carbon to the atmosphere.

Carbon Absorbed

Young, healthy forests absorb carbon more rapidly than older, dense forests. Older forests release carbon at the same rate that they absorb it, neutralizing their effect on global warming. Sustainably managing forests is an effective way to store carbon. Trees also produce oxygen that we all need.

Carbon Stored

As a tree grows, it stores carbon in its trunk, branches and roots. Sustainably managed forests continuously store and absorb carbon. Trees store carbon for a long time. When trees are harvested, the carbon continues to be stored in wood products. Harvested forests are replanted and the cycle begins again.

The Forest Foundation | www.calforestfoundation.org | 1-866-241-TREE

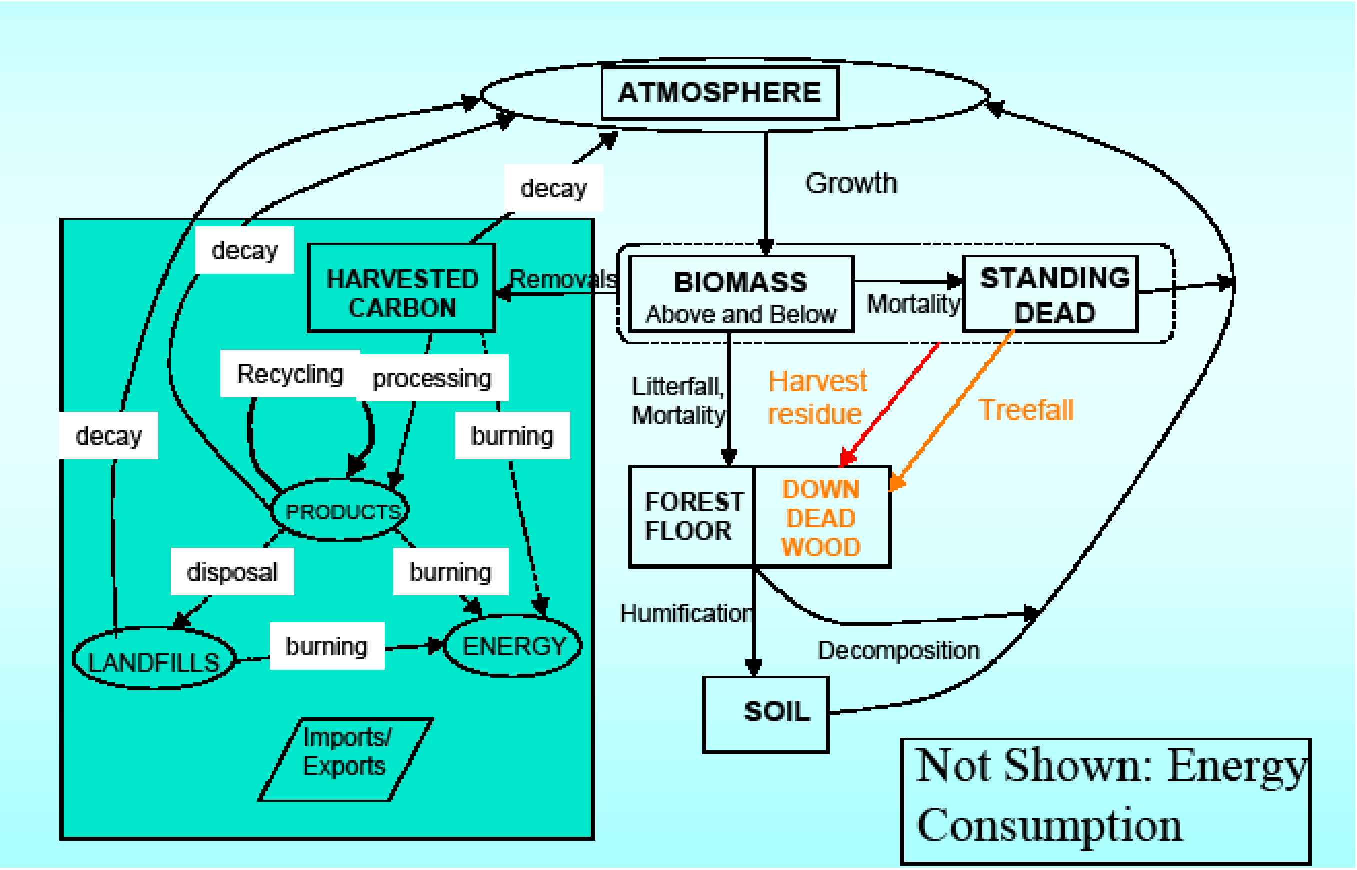


Figure 3. Significant carbon stocks and flows of California forests and forest products (from Heath and Birdsey 2000)**.**

Christensen and others (2007, Table 21) estimated that all California forests (above the ground only) store about 1,120.23 million bone-dry tons of carbon. More than half (785.51 million bone-dry tons) of stored carbon is on productive forest land not legally restricted from harvest, but most of that amount (418.89 million bone-dry tons) is on national forest land. About one-fifth is on forest industry land (161.0 million bone-dry tons). The forest types with the greatest amount of stored carbon are: California mixed conifer (460.8 million bone-dry tons), western oak (230.2 million bone-dry tons), fir/spruce/mountain hemlock (155.2 million bone-dry tons), tanoak laurel (135.0), and redwood (98.1) (Christensen et al. 2007, Table 22).

On average, the combined aboveground carbon storage of California forests is about 40 tons/acre (Christensen et al. 2007). Carbon accounting by forest type gives better estimates of the amounts captured because average carbon storage per unit area varies by forest type. For example, redwood forests, which produce the largest individual tree sizes, support the greatest concentration of carbon storage (150 tons/acre) among California forest types (Christensen et al. 2007, Figure 27). All hardwood types had less than half of that, with the greatest accumulations of carbon found in the tanoak/laurel (64 tons/acre) and the alder/maple (54 tons/acre) type groups.

California's largest forest carbon stocks are in soils (45 percent), followed by biomass (30 percent), and forest floor and coarse woody debris (20 percent) (Birdsey and Lewis 2002). In comparison, wood products and landfills contain about 6 percent of the forest carbon.

California's total forest carbon storage pool is distributed among five owner groups: National Forest (52%), Other Federal (8%), State and Local (5%), Forest Industry (15%), and Nonindustrial Private (20%) (Christensen et al. 2007, Table 21). Of these owner groups, national forest and other private showed average decreases of 1.05-2.65 million bone-dry tons/year in carbon storage over the 10-year period from 1987-1997 (Birdsey and Lewis 2002). Presumably, carbon loss from national forest and nonindustrial private ownerships resulted in large part from land use conversion and forest damage by insects, diseases, and catastrophic fires. While their carbon stores were being depleted, these ownerships were net sources of carbon to the atmosphere unless the carbon was captured and stored in other forms. In contrast over the same period, carbon storage on other public and forest industry ownerships showed increases of 4.09-5.70 million bone-dry tons/year, despite the regulated flow of harvested carbon to forest products (Birdsey and Lewis 2002). Comparable data for the last decade are not yet available.

Carbon Stocks and Flows among Actively Managed Forests

Forests are a crucial element for proactively managing atmospheric carbon and providing needed energy and other products for human consumption (Helms 2007a). Dr. John Helms describes the carbon management considerations and opportunities for California's forests better than anyone (Helms 2007b):

At the stand level, the amount of carbon sequestered by young trees varies between 2-6 tons of carbon per acre per year, depending on species and site quality. Starting from bare soil, the annual carbon uptake per acre per year of a planted stand culminates at between about 15 and 75 years, again depending on species and site quality. However, total accumulation of carbon (and wood) in fully stocked stands will continue to rise until the stand reaches maturity. Thus, young stands sequester carbon much more rapidly than older stands, which have less efficient photosynthesis and higher respiratory losses and, therefore, may ultimately have zero net CO_2 uptake but store more carbon.

Managing stands to enhance carbon sequestration requires focusing on ways to increase rates of leaf area production and maintain canopy cover. Over the long term, this requires active management of young stands with successive cycles of growing, thinning, and putting wood into either long-term use or products amenable to recycling or energy production. Rotation length influences the amount of time occupied by less-productive regeneration phases. Thinning temporarily reduces canopy cover, maintains stand vigor, captures mortality, and shifts carbon uptake to more-efficient growers. Consequently, various thinning methods yield differing carbon outcomes (Hoover et al. 2007). Not surprisingly, the selected silvicultural system (e.g., fully stocked, uneven-aged stands of mixed species; even-aged, single species stands) affects canopy continuity and leaf area, and the forest carbon cycle. Alternative site preparation treatments influence the amount of soil disturbance and the condition of logging slash, which affect soil temperature and the rate that carbon returns to the atmosphere. Fertilization increases leaf area production, and capacity to sequester carbon. Superior genotypes have more rapid leaf area production and greater CO_2 uptake.

Consequently, forest management choices influence carbon stocks and flows of California forests. The major long-term loss of potential carbon sequestration by forest land follows conversion to other land uses—the loss of forest carbon is about proportional to the acreage taken out of production. Landowners decide whether to maintain or convert every time they undertake forest management actions, after considering alternative returns on their investment. Conversion appears lucrative when the present net worth for alternative land uses exceeds timber production. Therefore, it is unsound to presume that forests will remain as forest forever, especially when other management options provide greater returns.

At a finer scale of management, the forester makes conscious decisions about silvicultural alternatives after evaluating biological potentials, economic constraints, and competing social values. Forests are unique in that no other means of sequestering or offsetting carbon has the added benefits of providing clean water, biodiversity, clean air, wildlife habitat, aesthetics, and needed products (Helms 2007a). However, managing forests to increase carbon sequestration and storage can lower benefits of certain other desired values.

Harvesting results in an immediate decline in the stand’s stored carbon, but the significance depends on the fate of the harvested carbon in various forest products and uses, and the environmental and carbon costs of using alternative products that require far higher amounts of energy for manufacture. Frequently trapping carbon in wood products can capitalize on the rapid growth of young trees to sequester carbon and more quickly create opportunities to replace the use of fossil fuel-intensive building materials like concrete or steel. Deductions account for energy consumed during timber harvesting activities, which include felling, processing (bucking, limbing, cutting to length), secondary transportation (skidding and yarding), loading, and hauling to a process point (Johnson et al. 2005).

Under sustained yield management, the forest is composed of individual managed stands such that the amount of carbon removed from the whole forest is roughly balanced by the amount of carbon grown. Therefore, carbon storage per acre across the forest remains stable, while harvested carbon flows to product pools (Eckert 2007).

Carbon Stocks and Flows among Unmanaged Forests

The decision to not manage forestland carries with it a responsibility for sacrificing full biological potential; at least as far as carbon management is concerned. Managed forests that incorporate a sequence of harvests result in more carbon sequestered than a forest left unmanaged, over the long term (Helms 2007a). Eckert (2007) showed that unmanaged forest stands, such as many in California’s national forests, sequester significantly lower amounts of carbon than intensively managed stands in the same area when both the standing forest and the harvested products are taken into account. Less intensively managed private forest stands, such as no-harvest buffers or extensively managed stands where selective harvest is the only permissible scheme, are intermediate in the amount of carbon sequestered (again, when both the standing forest and the harvested products are taken into account) (Eckert 2007). Old forests are less efficient in carbon sequestration, even without considering the carbon drain when trees are damaged or killed by disease, insects, or fire. Old forests store more carbon, but as they age the net uptake of carbon dioxide can diminish to zero as carbon lost in respiration and decomposition becomes similar to the rates of carbon uptake.

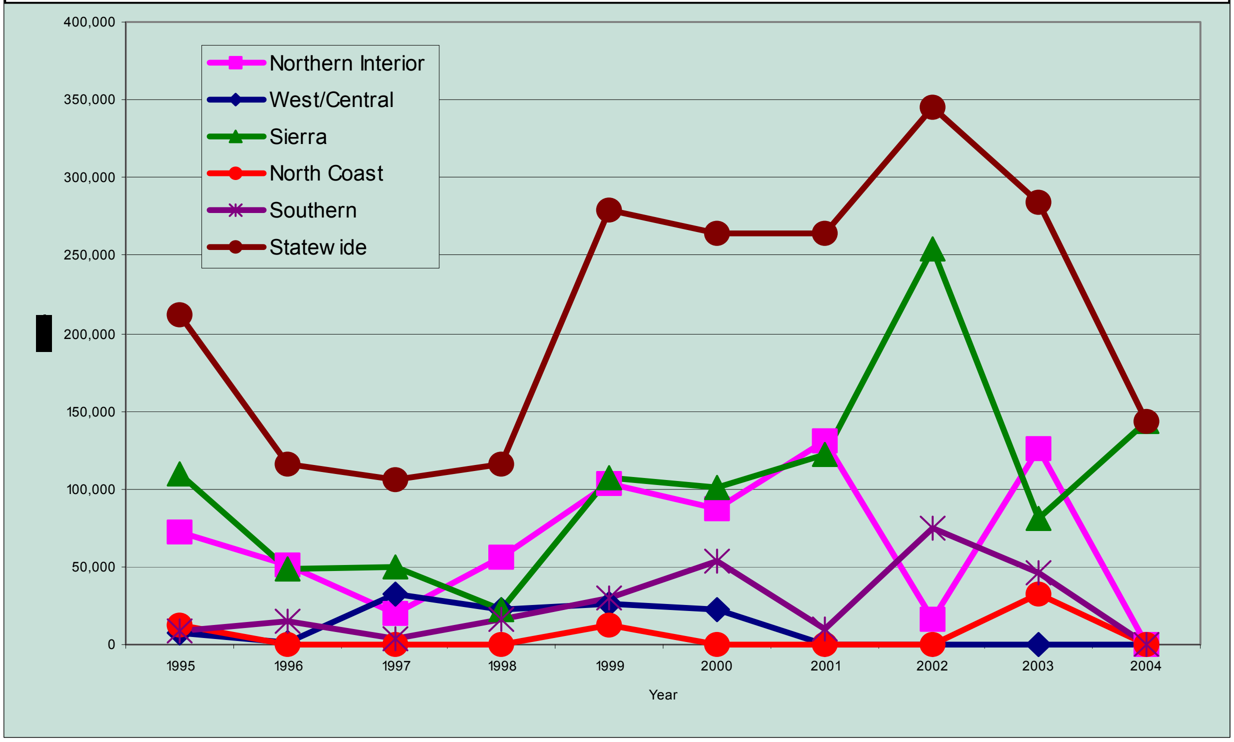
Tree harvesting is absent or infrequent in unmanaged forests. Consequently, forest practices do not cause immediate declines in carbon storage, and the fate of carbon in the various harvested products is untracked. However, the environmental and carbon costs of using alternative products that require far higher amounts of energy for manufacture is significant. Furthermore, deferred and excessively restricted harvesting (i.e., on national forests) is promoting excessive harvesting elsewhere, a carbon accounting process called leakage. Leakage is negative when carbon management within the project or service area causes compensation outside the area or causes carbon to be imported. Currently, the U.S. imports 36 percent of its wood consumption from other countries, some of which have far lower environmental standards and often may incorporate illegal logging (Helms 2007a). Californians are prodigious consumers of wood, importing 80 percent more than they produce (Tuttle 2007).

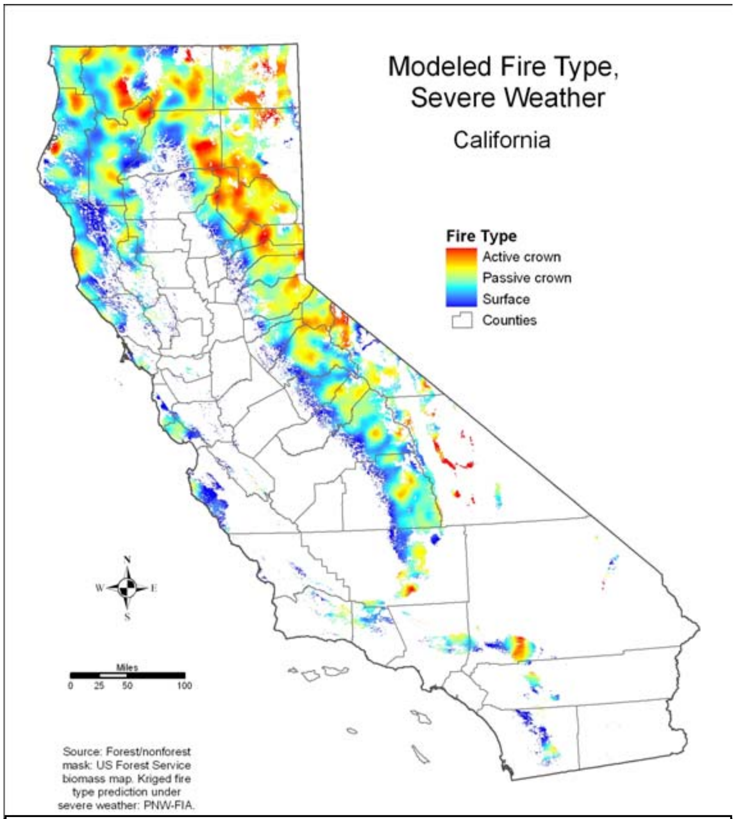
Wildfire Effects on Forest Carbon Stocks and Flows

By doing nothing in our forests, we are doing something—creating conditions that are far more conducive to unnatural, devastating crown fires than natural low-level surface flames. An important cause of carbon loss is catastrophic wildfires, especially in fire-adapted ecosystems such as those of the Sierra Nevada Mountains. Wildfires may emit up to 100 tons of CO_2 per acre depending on forest type, density, and fire intensity (Helms 2007b).

Across California, approximately, 5.5 million acres burned between 1990 and 2004, and more than 2 million acres burned between 2000 and 2006 (Kadyszewski and Brown 2006; Bonnicksen 2007). Under current conditions and fire policies, California forestland burns at the rate of about 213,000 acres per year, ranging from about 100,000 to 350,000 acres per year (Figure 4; Christensen et al. 2007).

Figure 4. Acres of forest burned by ecosection group in California: 1995 – 2004 (Christensen et al. 2007)





Source: Forest/nonforest mask: US Forest Service biomass map. Kriged fire type prediction under severe weather: PNW-FIA.

Figure 5. Fire and fuel hazard in California forests (Christensen et al. 2007). Red = greatest hazard, dark blue = least hazard.

Fire regime varies by ownership group, with state lands predicted to have the greatest percentage of forests in low hazard fire regimes and national forests having the least percentage in low hazard fire regimes (Christensen et al. 2007). Such differences almost certainly are due to differences in forest management, but also may be traceable to differences in age class structure, forest type, and stand history. Figure 5 shows the relative fire and fuel hazards for California forests (Christensen et al. 2007). In the figure, the greatest fire hazard is shown as red; the least is shown as dark blue. About 8 million acres of forest on California's national forests remain at high risk of catastrophic wildfire (Bonnicksen 2007).

Wildfires also remove carbon from surface soils and emit significant quantities of aerosols, particulates, and nitrous oxide and methane, which are more potent greenhouse gases than CO_2. Low intensity fires fail to kill the majority of the trees, but reduce fuel hazards for subsequent wildfires. Unnaturally dense forests provide fuel for unnaturally intense and large wildfires. High intensity fires are catastrophic in that they kill many trees, and convert much carbon stored as biomass to CO_2 emissions to the atmosphere.

Carbon in forests has five potential destinations during and after a fire (Brown et al. 2004). Some carbon will survive the fire to continue as live vegetation, some will be volatilized during the fire and immediately released to the atmosphere, and the remainder will be divided between the pools of dead wood, soot, and charcoal (Figure 6). Dead wood decomposes over time, but soot and charcoal are stable forms of carbon that can remain unchanged for very many years.

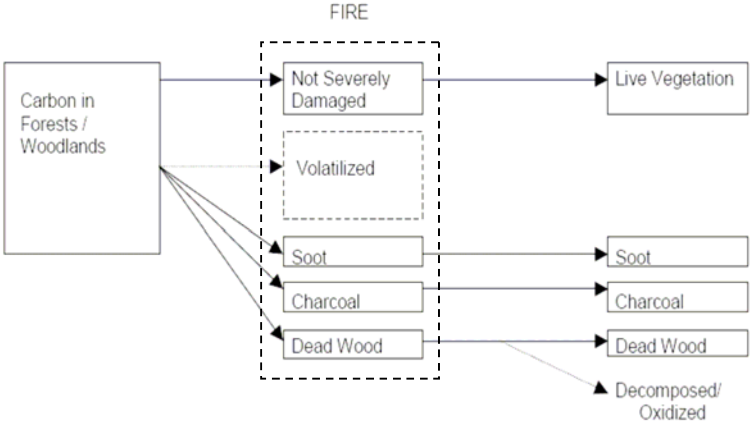


Figure 6. Carbon stocks and flows after forest fire (Brown et al. 2004).

Unmanaged forests are at greatest risk of losing large amounts of stored carbon to the atmosphere. Many California forests, particularly those on public lands, have grown dangerously overcrowded due to a century of fire suppression and decades of restricted timber harvesting. Significant emissions can be avoided through fire management, but management needs to be maintained through time to ensure permanency (Bird 1998).

Fire management is a benefit to the natural ecosystem because fire is part of the natural forest cycle. Prescribed burning and mechanical reduction are methods for reducing the fire hazard and risk of large carbon emissions (Helms 2007b). Prescribed burning typically does not affect soil carbon and limits carbon releases because it typically affects only understory plants and ladder fuels. Although prescribed burning returns some carbon, other greenhouse gases, and particulate matter to the atmosphere, combustion generally is more complete than wildfire, which releases higher concentrations of the other greenhouse gases and particulate matter.

Mechanical reduction of fuels reduces fire risk while yielding biomass for forest products or energy production. For instance, woody biomass obtained by reducing wildfire hazards can be used to produce cellulosic ethanol as an energy substitute (Helms 2007a). Furthermore, mechanical reduction avoids the direct carbon emissions of open burning.

Rapid salvage of damaged trees offsets potential carbon losses after wildfire. Up to 85 percent of the pre-fire merchantable volume can be recovered and stored as forest products (Eckert 2007). When catastrophes occur, burned areas can be promptly regenerated to ensure rapid restoration of forest cover. Prompt post-fire reforestation prevents shrubs and brush from reducing the leaf area and capacity for carbon sequestration.

Forest practices that reduce wildfire hazards or suppress fires may themselves consume carbon, although the amount of “leakage” during forest fuels management and fire suppression depends on the techniques used. The leakage should be calculated and deducted from the carbon savings. Leakage might include controlled burns of litter, deforestation to create fire breaks, and fossil fuel to combat fire. For example, heavy lift helicopters consume about 365 gallons/hour of fuel, which equals about 3.7 tons of CO_2 emissions per hour of operation. Air tankers have even higher fuel consumption.

Insect and disease infestations operate on forest carbon cycles similarly to wildfire, and exacerbate wildfire effects. Carbon pools drop precipitously from outbreaks. Dense, slow-growing unmanaged forest stands are most susceptible to attack, mortality, and rapid reduction of stored carbon. For example, bark beetles have thrived with the onset of unnaturally dense forests. In 2004 alone, insect outbreaks infested more than 1.7 million acres of national forest land in California, and experts predict more than 21 million additional acres of western forests will suffer significant tree mortality from bark beetle attacks during the next 15 years (Bonnicksen 2007).

Carbon Dynamics of California’s Forest Products

After tree harvest, long-term carbon storage is influenced by the manufacturing, use, and ultimate disposition of forest products. Figure 7 shows the major pathways that determine the carbon stocks and flows of forest products (Gustavsson et al. 2006). Carbon leaves the forest as round wood, fiber, and residues. Wood qualities determine the pathways and flows through sawmills and processing plants before reaching consumers as usable products such as lumber, molding and millwork, specialty products like medium density fiber board, and paper. Much of the wood waste generates energy through co-generation to power sawmills, produce excess electricity, or dry lumber. A relatively small amount of wood waste is converted to biofuel, and the remainder used as daily cover in landfills. Many products become recycled after fulfilling their initial function, which extends their utility. Eventually, worn out forest products generate energy or decay over surprisingly long periods of time in landfills.

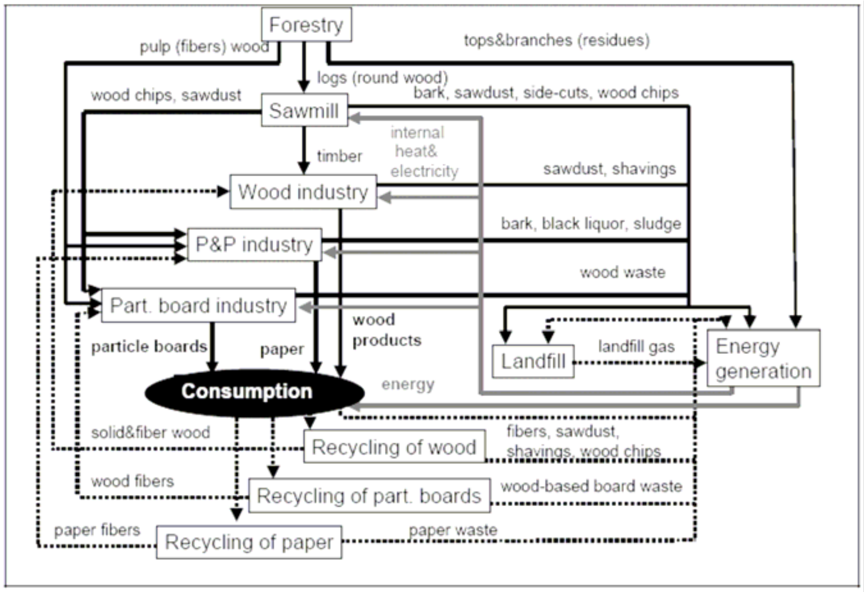


Figure 7. Carbon stocks and flows of forest products (Gustavsson et al. 2005)

Forest Products-In-Use

As previously described, the benefits of active forest management for carbon sequestration are more readily apparent after taking into account the carbon storage in wood products. Although the magnitudes of the carbon pools change over time, the contributions are additive and persistent, as shown in an example time series over two 80-year rotations (Figure 8).

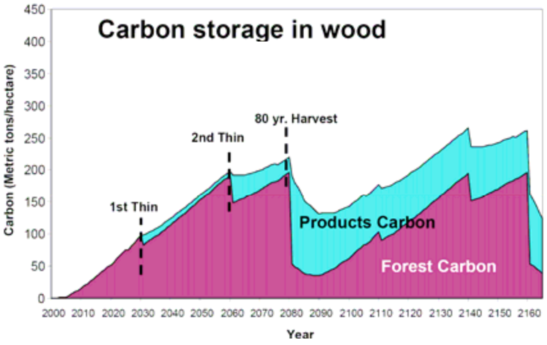


Figure 8. Carbon storage in forest products is a significant element of carbon accounting (Wilson (2006)

The fraction of harvested carbon converted to forest products depends on mill efficiency. In California, 70 percent of harvested carbon, on average, becomes stored in manufactured forest products (Eckert 2007). The 30-percent balance generates energy. Mill efficiency is an important factor determining the overall carbon management performance of actively managed forests.

The amount of carbon stored in forest products declines gradually over time, even with recycling and reuse, but much remains functional even after 100 years. Durable solid wood and particle board products (i.e., saw wood, veneer, plywood and structural panels, and non-structural panels) cycle more slowly than paper products (Penman et al. 2003; Skog and Nicholson 1998). Skog (2007) calculated a 40-year weighted average of the half-lives used for various solid wood products.

The treatment of wood-based products at their end of life has important CO_2 implications. Wood-based products might be used for energy purposes, recovered for other material applications (recycled or reused), or landfilled as solid waste. When forest products are recycled, carbon remains stored in forest products without increasing forest consumption.

Product Substitution

Wood substitution in carbon management is the use of forest biomass (wood) to replace other products emitting more CO_2 per service or functional unit. Substitution occurs by using wood instead of non-wood materials (i.e., material or indirect substitution). Net emissions account for fossil fuel use over the life cycle of the products (e.g., production, transportation, end-use and waste management of a product) and industrial process reactions (e.g., cement and steel production). Wood substitution has the greatest long-term potential for reducing CO_2 emissions, by focusing on the transfer of biomass carbon into products that substitute for or reduce the use of fossil fuels, rather than on increasing the carbon pool itself. However, wood substitution affects and is affected by a number of technical, economic, and social factors that change over time and space.

Wood is a versatile material. The most important materials competing with wood are plastics, aluminum, steel, concrete, gypsum, and brick (Gustavsson et al. 2006). Steel, concrete, and brick are important alternatives in construction. Aluminum and plastics are widely used in manufacturing of windows and doors, and in the packaging sector. CORRIM and NCASI studies show wood to be the lowest greenhouse gas emitter compared to steel, concrete and other building materials in life cycle analyses comparing embodied energy and carbon emissions (NCASI 2006). Alternative materials (concrete, steel) for wood are much more fossil-fuel-intensive in their production and use, and substituting for them, as wood products do, reduces carbon emissions to the atmosphere. Life cycle assessments show that the energy-intensive alternatives to wood require as much as 250 percent more energy to produce than an equivalent amount of wood product, and they are not renewable (Lippke et al. 2004).

The benefits of intensive forest management are strengthened if the value of the wood product as fossil-fuel-intensive material substitution is taken into consideration. Perez-Garcia and others (2005) concluded that forest products lead to a significant reduction in atmospheric carbon by displacing more fossil fuel-intensive products in housing construction. They showed that wood is less costly in energetic terms than substitute materials, including full calculations of energy investments from harvest through final product preparation. When viewed on a life cycle-basis, wood-based building materials are substantially less carbon intensive than substitute materials.

Wood for Wood Substitution

Carbon life cycle analysts note that carbon storage and energy consumption vary among alternative wood products used for the same function. These material substitutions, a behavior known as within-wood substitution, may create significant efficiency gains when wood use is traced back to the forest land base.

For example, green lumber requires four percent less energy and shows two percent less global warming potential compared to kiln-dried lumber for studs in construction (Lippke et al. 2004). Compared to oriented strand board (OSB), plywood substitution has a three percent lower environmental burden for a completed house (Lippke et al. 2004). However, OSB is produced from wood of several species that are generally considered to be of lower value relative to plywood. Consequently, OSB production reduces the demand for higher quality wood, which substantially increases forest productivity and carbon storage in wood products, and reduces residues.

Engineered I-joists use only 62-65 percent of the wood required by solid-sawn joists for the same purpose. Although they store less carbon, I-joists substituted for solid-sawn wood joists may have very little difference in environmental performance indices because the greater material efficiency of the I-joists is offset by the increased use of resins and energy (Lippke et al. 2004). However, the I-joists benefit long-term carbon storage by routing a greater percentage of harvested carbon to durable wood products. Like the OSB substitute for plywood, I-joists are made of OSB, which incorporates lower valued tree species and lesser qualities of wood, compared to solid wood joists.

Imports/Exports

As stated previously, Californians are prodigious consumers of wood and import 80 percent more than they produce, much of it from places with fewer environmental protections (Tuttle 2007). The carbon leakage through imports and exports may be positive or negative, and depends on the carbon source and reference area. Deferred harvesting and resulting importation of wood products or energy-intensive wood substitutes causes negative leakage (relative to the forest carbon pool) because it results in net carbon losses. Positive carbon leakage occurs through greater use of local wood products in the market place to reduce imports and less-efficient wood substitutes. Environmental equity would argue for California to produce more of our own wood products and promote the corresponding climate benefits and air quality.

Products Disposed in Landfills

Eckert (2007) depicts carbon's fate in forest products during the years after harvest (Figure 9). The fraction of harvested carbon converted to forest products depends on mill efficiency—70 percent, on average, in California. The 30-percent balance generates energy. Landfill carbon stocks rise as forest products wear out, but then level off as inputs balance losses through decomposition. The net effect is a gradual decline of carbon stored in product and landfill combined, over the long term.

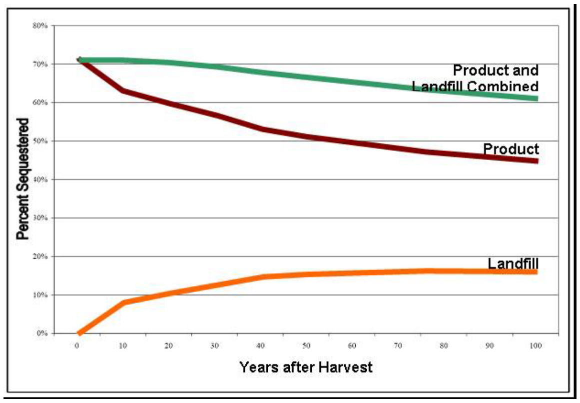


Figure 9. Long-term fate of carbon in CA forest products (Eckert 2007)

There are currently large stocks of carbon in dumps and landfills, and the size of these carbon stocks is increasing (Skog and Nicholson 2000). The stocks and flows of carbon in landfills change over time as our patterns of wood use change. By understanding the carbon dynamics of the forest products waste stream, we are better able to manage carbon resources and more fully attribute the carbon sequestration benefits of active forest management, which endure beyond the useful product life.

The internal landfill environment is heterogeneous, and many factors influence the production and emission of CO_2 and other gases, such as methane (CH_4) (Barlaz 2004). Figure 10 shows the chemical pathways of anaerobic decomposition in landfills that eventually lead to carbon emissions. Factors influencing the rate of decomposition in landfills include: (1) waste management and processing variables, such as the size of the waste particles (i.e., whether the material is shredded, crushed, or bailed); (2) the composition of the waste; (3) factors that influence bacterial growth, such as moisture, available nutrients, pH, and temperature; (4) the design of the landfill and whether landfill gases are contained or extracted (for flaring or for energy production); and (5) the operation of the landfill, including the amount of compaction, the type and thickness of covering materials, the amount of natural moisture from precipitation or groundwater, and whether the leachate is recycled or removed for treatment (Micales and Skog 1997).

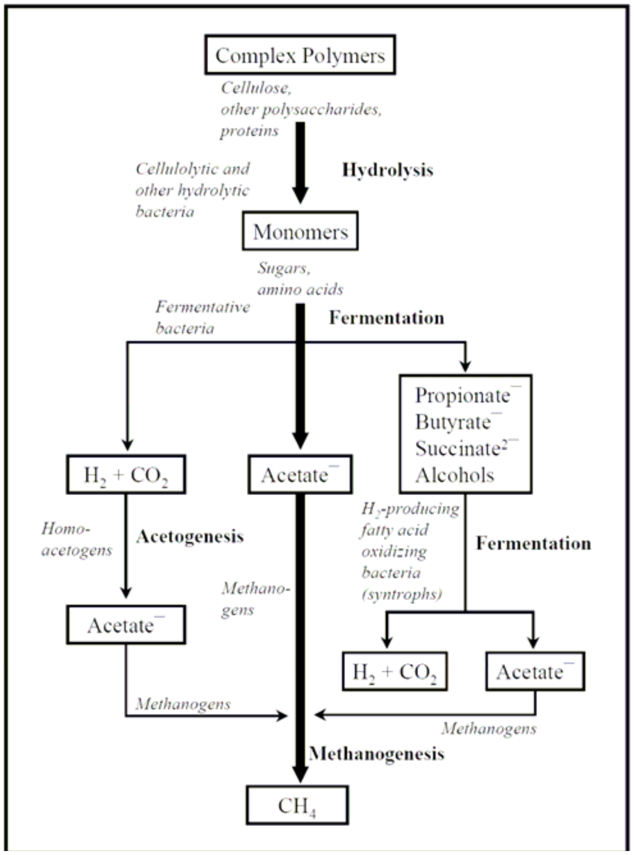


Figure 10. Anaerobic decomposition in landfills that ultimately leads to release of methane and carbon dioxide (Barlaz 2004)

Landfills serve as a tremendous carbon sink, effectively preventing major quantities of carbon from being released back into the atmosphere. Only a fraction of the landfilled wood is decomposed—only 26 percent of the carbon from paper, on average, and 0-3 percent of the carbon from wood are ever emitted as landfill gas (Micales and Skog 1997). The carbon remainder becomes sequestered in the landfill for a long time (i.e., longer than 40 years). Therefore, the net impact of landfills on carbon depends on decomposition conditions within the landfill and utilization of landfill gas in place of fossil fuels, but most is stored indefinitely. Methane gas can be collected and used to substitute for fossil fuels.

As an alternative to landfills, energy substitution using wood products waste reduces greenhouse gas emissions in the way that residues from tree harvesting and wood processing do, as described above. As much as 15–20 percent of the solid waste traditionally disposed of in U.S. landfills is clean wood waste that can be segregated and converted into fuel for power generation (Morris 1999).

Fossil Fuel Displaced by Forest Products

Displacement (substitution) occurs by using wood instead of fossil fuels. Wood substitution for energy generation has long-term potential for reducing CO_2 emissions by reducing the use of fossil fuels, rather than increasing the carbon pool itself. Biomass fuels are fundamentally different from fossil fuels because biomass fuels recycle carbon to the atmosphere whereas fossil fuels introduce new carbon to the atmosphere. This is why biomass fuels are called carbon-neutral. The forest industry is energy intensive, but meets most of its needs with carbon-neutral biomass fuels.

Biomass can reduce CO_2 through energy substitution because fossil fuel is an associated carbon sink (Schlamadinger et al. 2001). When biomass energy substitutes for fossil energy, the substitution has a direct effect on greenhouse gas emissions. Although bioenergy is often considered CO_2 neutral, the use of carbon for the purpose of biomass energy could have positive, negative, or neutral impacts on the stock of biospheric carbon because biomass energy pathways differ greatly in the timing and nature of their carbon flows (Schlamadinger et al. 2001). However, it is likely that co-generation of energy from wood waste by California's forest products industry would be positive (Bowyer et al. 2004).

More than sixty solid-fuel fired biomass power generating facilities have operated in California since 1980, with a combined generating capacity of almost 1,000 MW (Morris 2007; Morris 2002). Presently, California's biomass energy producers generate 1.5–2 percent of California's electricity while consuming more than 4.6 million bone-dry tons of biomass waste annually (California Biomass Collaborative 2005). Much of the biomass waste used by power generating facilities to produce energy comes from residues of forest practices and forest products. Residues arise from forest felling and thinning, and industry processes for consumables. As mentioned above, approximately 30 percent of the harvested carbon from California's forests is used for energy production. Potentially, short rotation woody forest crops can be managed explicitly for energy production, but this practice is uncommon in California. The greater opportunity is for forest fuels management and wildfire prevention.

Life Cycle Analysis for Forest and Forest Products—Putting It All Together

Perez-Garcia and others (2005) used life cycle analysis and constructed an accounting scheme that considered carbon from forests to end-use markets of forest and competing products. The accounting scheme combined three carbon pools: the forest pool, the product pool, and the product substitution or energy displacement pool. This last pool included the energy-use and carbon-emission implications of competing products.

As wood is harvested and converted to durable products, the carbon remains stored over the long term. Figure 11 shows an example of carbon sequestration by forest over two 80-year forest management cycles, which minimally is the sum of the carbon stored in the three pools (Lippke et al. 2004). The major benefit of forest and wood products is realized only after the opportunity costs of using fossil fuel-intensive wood substitutes are considered, making the total

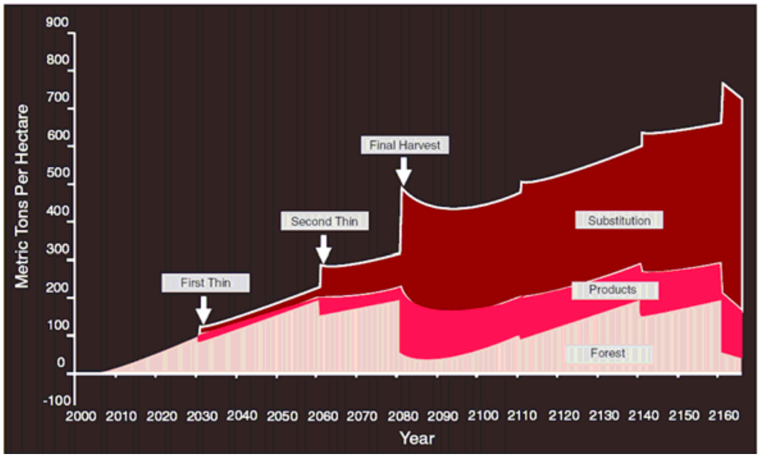


Figure 11. Carbon storage in forest and forest product pools, including the product substitution or energy displacement pool (Lippke et al. 2004)

value of carbon removal by forests and forests products more apparent. Figure 12 illustrates the relative emission factors associated with carbon leakage by harvesting and processing forest resources (Lippke et al. 2003). In the figure, fuchsia = harvest emissions and dark blue = manufacturing emissions; both are shown as negative credits against total carbon sequestration. The costs and consumption rates of energy and materials for these activities partly drive the wood outputs, emissions, and carbon pools (Johnson et al. 2005).

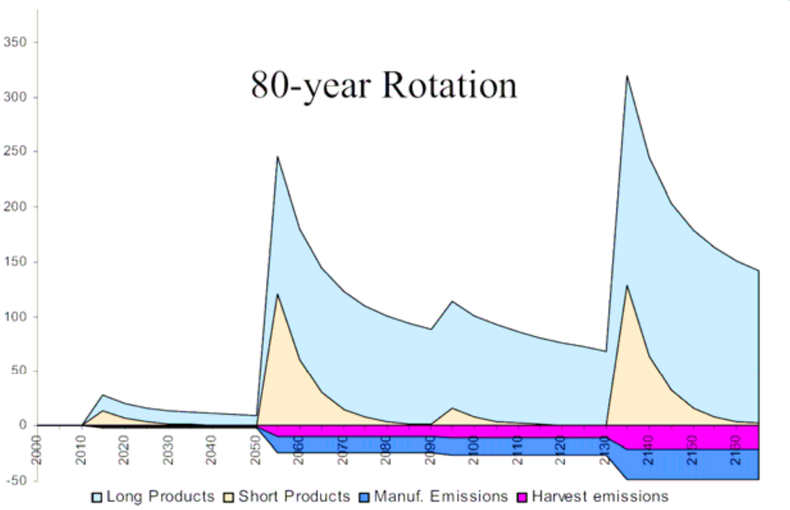


Figure 12. Relative carbon leakage due to harvest and manufacturing emission factors (Lippke et al. 2003)

Consistent with Eckert (2007), Perez-Garcia and others (2005) showed that shorter forest harvest cycles <u>reduce</u> net carbon emissions into the atmosphere (compared to long rotations or no management). Forests managed under short rotations may or may not sequester more carbon than forests managed over longer rotations—performance depends on forest productivity, mill efficiency, product uses, etc.—but all agree that intensively-managed forests outperform when the avoided and displaced emissions associated with production and use of energy-intensive, competing products are taken into account. The shorter cycles produce more wood products sooner, thereby reducing fossil fuel-intensive substitutes earlier in time. The avoided emissions through product substitution generally exceed carbon sequestration benefits of forest attributable to a longer harvest cycle or unmanaged forest. The net result is that more carbon is sequestered in the forest and wood products under short rotations when the embodied energy pool is included.

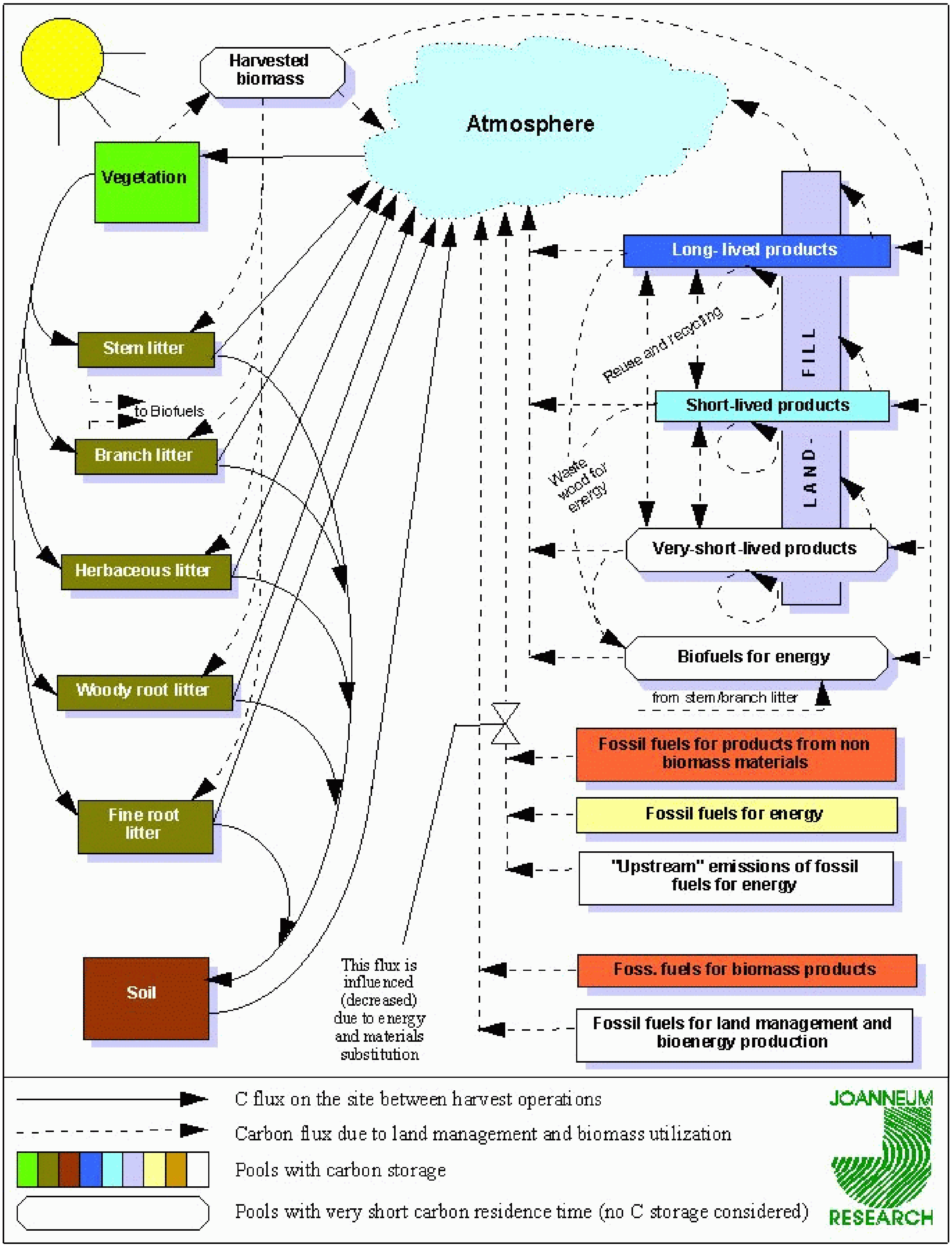
Quantifying Carbon Stocks and Flows

Options for quantifying the carbon cycle range from relatively simple estimates based on default factors to data intensive modeling approaches, some based on detailed inventories. Available protocols for carbon inventorying, accounting and reporting appear cumbersome and expensive to apply, especially for California's forest resources (Mader 2007).

Many have attempted to model the forest and forest products carbon cycle. The modeled estimates of stocks and flows vary by the elements they include, their reliability, and spatial applicability. One example is GORCAM, a spreadsheet model that attempts to keep account of all of the carbon stocks and flows impacted by forest management decisions (Figure 13; Schlamadinger et al. 2007).

The USDA-Forest Service has developed the WOODCARB model to simulate carbon flows associated with forest products, and has published estimates of carbon content and decay rate of various wood products (Miner 2006). Another model is the Carbon On-Line Estimation (COLE)

Figure 13. Carbon stocks and flows described by the GORCAM model (Schlamadinger et al. 2007).



tool, an accepted model with potentially broad geographic application (available at: http://ncasi.uml.edu/COLE/), although still a work in progress. Plans are to update COLE's user interface to address the U.S. Department of Energy's 1605(b) reporting requirements more directly, and to ensure that its calculations match the 1605(b) Technical Guidelines (DOE 2006; Birdsey 2007). Also, the California Air Resources Board is in the process of developing a comprehensive forestland carbon life-cycle model to validate annual in-state CO_2 emissions.

Flexibility of tools and methods is important for promoting fair and equitable reporting, and avoiding disincentives for carbon management due to exorbitant cost. The 1605(b) guidelines, for example, recognize the benefits of a non-prescriptive approach to accounting methods and of offering scalable accounting procedures, with varying levels of reliability, to match each owner's prevalent inventory practices, implementation resources, and documentation requirements (DOE 2006).

The following sections offer equations and conversion factors suited to California forests and forest products that will aid carbon reporting and registration processes.

Carbon in Forests

Carbon Equivalents

Measures of carbon emissions and reductions typically are expressed in the form of carbon dioxide equivalent. Carbon dioxide equivalent is the weight of the gas, which is higher than the weight of the carbon alone because the gas also includes oxygen atoms. Multiply the weight of carbon x 3.67 to yield carbon dioxide equivalent.

Basic Carbon Stock Equation

To calculate the quantity of carbon in an area of forest:

$$I = A \times C/\text{acre}$$

Where:
I = inventory of carbon stock
A = area in hectares
C/acre = quantity of carbon stored per acre (in tons per acre); may include an estimate of harvested wood products)

Equation for the Stock-Change Approach

Carbon flows from forests and forestry operations are typically estimated using changes in an inventory of carbon stocks:

$$\text{Net annual carbon stock change in year } t = (I_t - I_{t-1})$$

Where:
I_t = inventory of carbon stock (in mass units such as tons) in the forest area in year t
I_{t-x} = inventory of carbon stock (in mass units such as tons) in the forest area in the year immediately preceding t (stock-change estimates often use longer time intervals)

Average Carbon Stock-Change

$$\text{Net average annual carbon stock change} = (I_t - I_{t-5})/5$$

Where:

I_{t-5} = inventory of carbon stock in the forest area 5 yrs (for example) before the current year

I_t = inventory of carbon stock in the forest area in the current year

Forest Carbon Estimation Tools and Assumptions

Carbon reporting may be complicated, but available tools and assumptions make the job easier. A primary resource is the Technical Guidelines of the DOE's 1605(b) program (DOE (2006). The Technical Guidelines devote an entire appendix to tables, decay-rate equations and default coefficients that can be applied to forest inventory estimates and harvest volumes, or wood product statistics to estimate carbon stored in wood products after harvest. Regional data applicable to California are found under the forest ecosystem category, "Pacific Southwest" (PSW).

Carbon reporting protocols often encourage reporters to use alternative carbon estimation methods (e.g., custom look-up tables) if the methods cover new information sources, provide more accurate results, or may be more cost effective for the reporter's specific circumstances. Typically, the reporter must submit a description of the method, an explanation of how the method is implemented, and evidence of the method's validity and accuracy. The following sections suggest some alternative tools and assumptions for use in California.

Typical Intensive Timber Harvest in California

Commercial Thinning. Performed at age 40-50, on average.

Rotation Length. 80-year cycle, on average (Eckert 2007).

Silvicultural System. Even-aged forest management (i.e., clearcut or seed tree); hand planted (Eckert 2007).

Carbon Sequestration Rate.
Managed 40-50 year old ponderosa pine (site class $100_{\text{50 year base}}$) = 3.24 tons C/acre/year. [Approximately 80% of Sierra Pacific Industries' total timberland in California is classified as site class 100 (Eckert 2007)]

Typical Extensive Timber Harvest in California

Commercial Thinning. Not performed.

Rotation Length. 90-year cycle, on average (Eckert 2007).

Silvicultural System. Selective harvest; 1 (or 2) selective harvests per 90 years, removing 50-67% of the merchantable volume (Eckert 2007).

Carbon Sequestration Rate.
Unavailable; less than intensive management.

Typical Fuel Management in California

Forest Product Yield. Mechanical fuel reduction may produce bioenergy or commercial products, depending on forest structure. Average harvesting density = 30 tons/acre (16.5 bone dry tons/acre) per treatment cycle (Morris 1997).

Fuel Treatment Cycle. Fuel reduction treatments are performed at about 15-year intervals.

Carbon Storage

Aboveground and Belowground Biomass based on Merchantable Tree Volume

Total tree volume per acre (above- and belowground) = Merchantable standing cubic feet per acre * 1.675 (Haswell 2000; Cairns et al. 1997; Eckert 2007).

Powers and others (2005) indicate that bolewood is about 53 percent of total tree biomass, and that belowground biomass is about 25 percent of total tree biomass in California mixed conifer.

Total carbon (pounds per acre) in standing tree volume = Total tree volume per acre (above- and belowground) * [13.29 lb/ft^3 for ponderosa pine; 14.20 lb/ft^3 for mixed conifer; or 15.11 lb/ft^3 value for Douglas-fir] (Haswell 2000; Eckert 2007).

Carbon in Understory Vegetation (Shrubs and Grasses Combined, within Forest and Woodland)

Shrubs and grasses = 8.92 tons C/acre (Brown et al. 2004).

Understory vegetation = 2% of the above- and belowground tree biomass density (Brown et al. 2004).

Standing Dead Trees

Standing dead trees = Use equations from Smith and others (2003).

Carbon in Soil

Carbon in soil (constant) = 81,191 lb/acre (Haswell 2000).

Brown and others (2004) assume changes in the soil carbon pool are slow and of a small magnitude.

Carbon in Litter

Carbon in litter (constant) = 23,061 lb/acre (Haswell 2000).

Litter and downed dead wood adds either 7% (Douglas-fir, redwood, other conifer), 10% (hardwoods), or 15% (fir-spruce) (Brown et al. 2004).

Wildfire

Fire Frequency

Fire frequency and severity across all managed and unmanaged ownerships in the Sierra Nevada area are shown in Table 1.

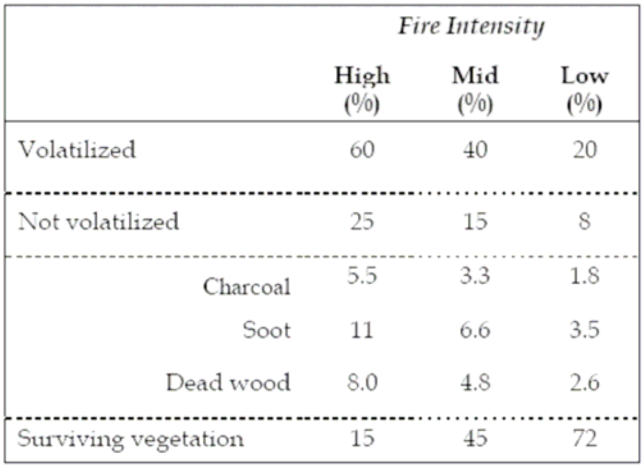
Table 1. Sierra Nevada Framework fire frequency and severity (Eckert 2007, after Klaus Barber, USFS, 8/5/2003)

Stratum/Type	Frequency per decade	Percent stands removed	Percent stands partly damaged (assume 50% mortality)
Ponderosa pine	6%	38%	31%
Mixed conifer	4%	46%	21%
White fir	2%	49%	18%
Hardwoods	6%	5%	85%

Actively managed forests with fuels management generally exhibit below-average fire frequency. For example, the largest private forestland owner in California experienced a 2.3 percent fire frequency per decade between 1987 and 2004, over mostly ponderosa pine and mixed conifer types below 6,000 feet elevation (Eckert 2007).

Post-Fire Carbon Flows. Fire intensity determines the relative amount of vegetation killed by the fire, and the proportions transformed to volatilized gases or non-volatilized forms (McNaughton et al. 1998; Carvalho et al. 2001). Table 2 simplifies the complexity of fire ecology and shows proportional shifts among carbon pools for the volatilized, non-volatilized, and surviving (living) pools of forest carbon (Comery 1981; Raison et al. 1985; Fearnside et al. 1993; Neary et al. 1996; Brown et al. 2004). Brown and others assume that dead wood decomposition occurs for two years from the fire-occurrence, and that decomposition occurs at a rate of 0.05 yr^{-1} (Harmon et al. 1987; Chambers et al. 2000).

Table 2. Assumptions for the fate of carbon after fire-induced decreases in canopy coverage (Brown et al. 2004)



	Fire Intensity		
	High (%)	Mid (%)	Low (%)
Volatilized	60	40	20
Not volatilized	25	15	8
Charcoal	5.5	3.3	1.8
Soot	11	6.6	3.5
Dead wood	8.0	4.8	2.6
Surviving vegetation	15	45	72

Salvage. Rapid salvage of damaged trees offsets potential carbon losses after wildfire. Up to 85 percent of the pre-fire merchantable volume can be recovered and stored as forest products (Eckert 2007). Additional salvaged carbon goes toward energy production.

Carbon in Forest Products-In-Use

Additional accounting is required for carbon in wood that is removed from the forest. Greenhouse gas emission calculation tools are available for calculating carbon emissions from pulp and paper and from wood product manufacturing—see www.ghgprotocol.org. Each tool comprises a guidance section and automated worksheets. All calculation tools have been peer-reviewed and tested by experts and industry leaders and represent a "best practice" for emission calculation tools.

Miner (2006) points out the difficulties associated with national carbon accounting methods. The preferred method is called the 100-year method, which estimates the amount of carbon in products expected to remain in use for at least 100 years. Instead of estimating changes in current stocks of carbon in products-in-use, it estimates future changes in these stocks attributable to current production. Under the 100-year method, current year additions to stocks of carbon in products-in-use are netted against future losses from current year additions. The result is the amount of carbon in the current year's production that is expected to remain in-use for a defined period of time. The calculations for each year's production are independent of past years' production, so the method is free of a "start up effect," which is problematic for corporate accounting. Alternative methods are not designed to produce realistic estimates of the amount of product remaining in use for 100 years.

Miner (2006) describes the steps and equations for the carbon accounting of forest products using the 100-year method. The five steps are:

1. Identify the types and amounts of biomass-based products (e.g., softwood lumber) that are made in the year of interest and end up in a final product (e.g., homes).
2. Express this annual production in terms of the amount of biomass carbon per year for each product.
3. Divide the products into categories based on function and allocate the carbon to the functional categories. Some of the functions for softwood lumber, for instance, would be single-family homes, home repair, multifamily residences, shipping containers, and railroad ties. Alternatively, products can be divided into the categories used for national and international harvested wood products accounting.
4. Use decay curves or other time-in-use information to estimate the fraction of the carbon in each functional category, expected to remain in use for 100 years.
5. Multiply the amount of carbon in annual production in products in each functional category by the fraction remaining at 100 years. The result is the amount of sequestered carbon in the products in each functional category attributable to this year's production.

The 100-year method of carbon accounting uses decay curves of Row and Phelps (1996) to estimate the fraction of carbon remaining in use after 100 years. The method is sensitive to the selection of time-in-use distributions (i.e., half-lives for specific end uses of forest products); see examples below.

Mill Efficiency in California

Total harvested wood volume from California forests converted to product = 70% (range = 68% (small log mills) to 71% (large log mills)) (Eckert 2007)

Total harvested wood volume from California forests converted to energy in a co-generation facility = 30% (range 29% to 32%) (Eckert 2007)

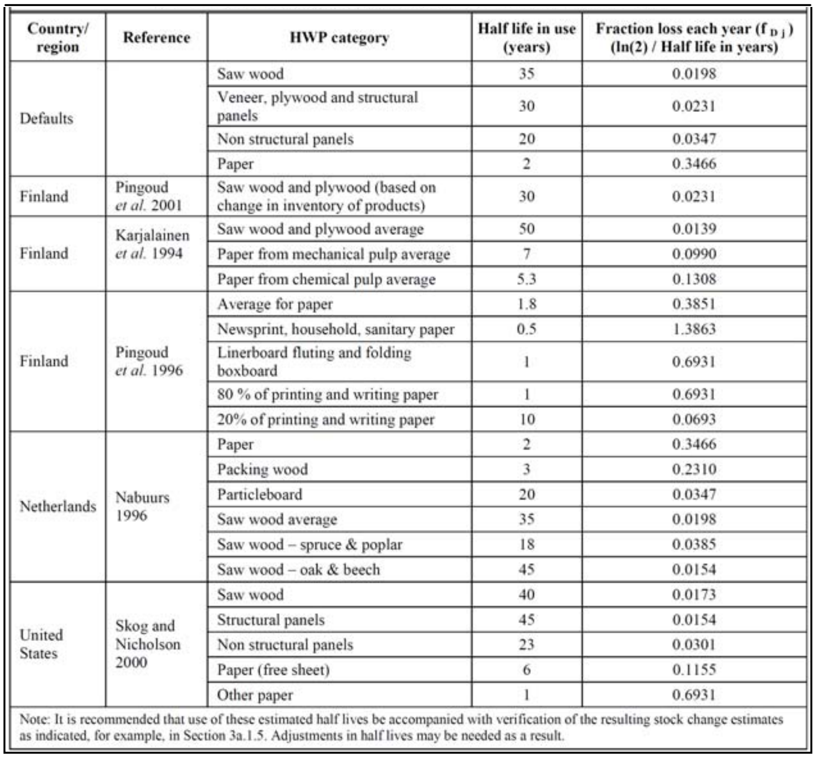
Sawmill residue (biomass) = 1.43 bone dry tons/thousand board feet (BDT/MBF) (California Biomass Collaborative April 2005)

Losses in converting primary wood products to final products = 8% (Skog and Nicholson 1998)

Half-Lives of Forest Products

The time of carbon storage in wood products is expressed as half-life, which is the time required for half the quantity of carbon in a wood product to be transformed or eliminated by normal use. Half-life estimates for wood product types are shown in Table 3 (Penman et al. 2003). The estimates of Skog and Nicholson (2000) are for the United States, and generally are longer than the international default values. The DOE (2006) published a varying set of half-life values of wood products for the 1605(b) Program (Table 4), and Skog (2007) more recently calculated a 40-year weighted average of the half-lives used for various solid wood products in the United States.

Table 3. Half-life of harvested wood products-in-use (Penman et al. 2003)



Country/ region	Reference	HWP category	Half life in use (years)	Fraction loss each year ($f_{D\,j}$) (ln(2) / Half life in years)
Defaults		Saw wood	35	0.0198
		Veneer, plywood and structural panels	30	0.0231
		Non structural panels	20	0.0347
		Paper	2	0.3466
Finland	Pingoud *et al.* 2001	Saw wood and plywood (based on change in inventory of products)	30	0.0231
Finland	Karjalainen *et al.* 1994	Saw wood and plywood average	50	0.0139
		Paper from mechanical pulp average	7	0.0990
		Paper from chemical pulp average	5.3	0.1308
Finland	Pingoud *et al.* 1996	Average for paper	1.8	0.3851
		Newsprint, household, sanitary paper	0.5	1.3863
		Linerboard fluting and folding boxboard	1	0.6931
		80 % of printing and writing paper	1	0.6931
		20% of printing and writing paper	10	0.0693
Netherlands	Nabuurs 1996	Paper	2	0.3466
		Packing wood	3	0.2310
		Particleboard	20	0.0347
		Saw wood average	35	0.0198
		Saw wood – spruce & poplar	18	0.0385
		Saw wood – oak & beech	45	0.0154
United States	Skog and Nicholson 2000	Saw wood	40	0.0173
		Structural panels	45	0.0154
		Non structural panels	23	0.0301
		Paper (free sheet)	6	0.1155
		Other paper	1	0.6931

Note: It is recommended that use of these estimated half lives be accompanied with verification of the resulting stock change estimates as indicated, for example, in Section 3a.1.5. Adjustments in half lives may be needed as a result.

Table 4. Half-life for products by end use (DOE 2006)

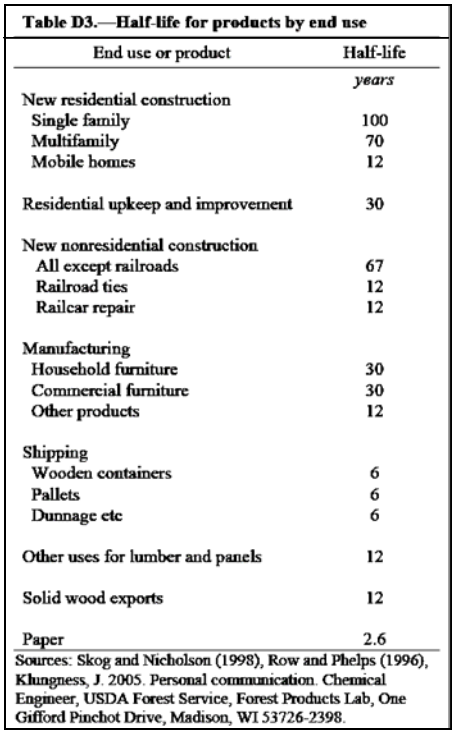


Table D3.—Half-life for products by end use

End use or product	Half-life
	years
New residential construction	
Single family	100
Multifamily	70
Mobile homes	12
Residential upkeep and improvement	30
New nonresidential construction	
All except railroads	67
Railroad ties	12
Railcar repair	12
Manufacturing	
Household furniture	30
Commercial furniture	30
Other products	12
Shipping	
Wooden containers	6
Pallets	6
Dunnage etc	6
Other uses for lumber and panels	12
Solid wood exports	12
Paper	2.6

Sources: Skog and Nicholson (1998), Row and Phelps (1996), Klungness, J. 2005. Personal communication. Chemical Engineer, USDA Forest Service, Forest Products Lab, One Gifford Pinchot Drive, Madison, WI 53726-2398.

Wood Products Substitution

The DOE Technical Guidelines provide methods for estimating the effects of wood products substitution of manufactured products. See the Technical Guidelines for the manufacturing sector (DOE 2006). Also, see methods used by Bowyer and others at CORRIM (2004; http://www.corrim.org/reports/).

Recycling

Recycling affects the length of time carbon remains in the use phase. The higher the utilization rate (the fraction of the product reused to make new product), the longer the carbon remains in use. The relationship is often described using the following equation (Row and Phelps 1996):

Time in use with recycling =
time in use without recycling/(1-utilization rate)

(Accordingly, recycling 20 percent of a product back into a new product increases its time in use by 25 percent and recycling 50 percent back into a new product doubles the time in use.)

Recycling rates in the U.S. for all materials categories in 2005 are listed in Table 5 (EPA 2006).

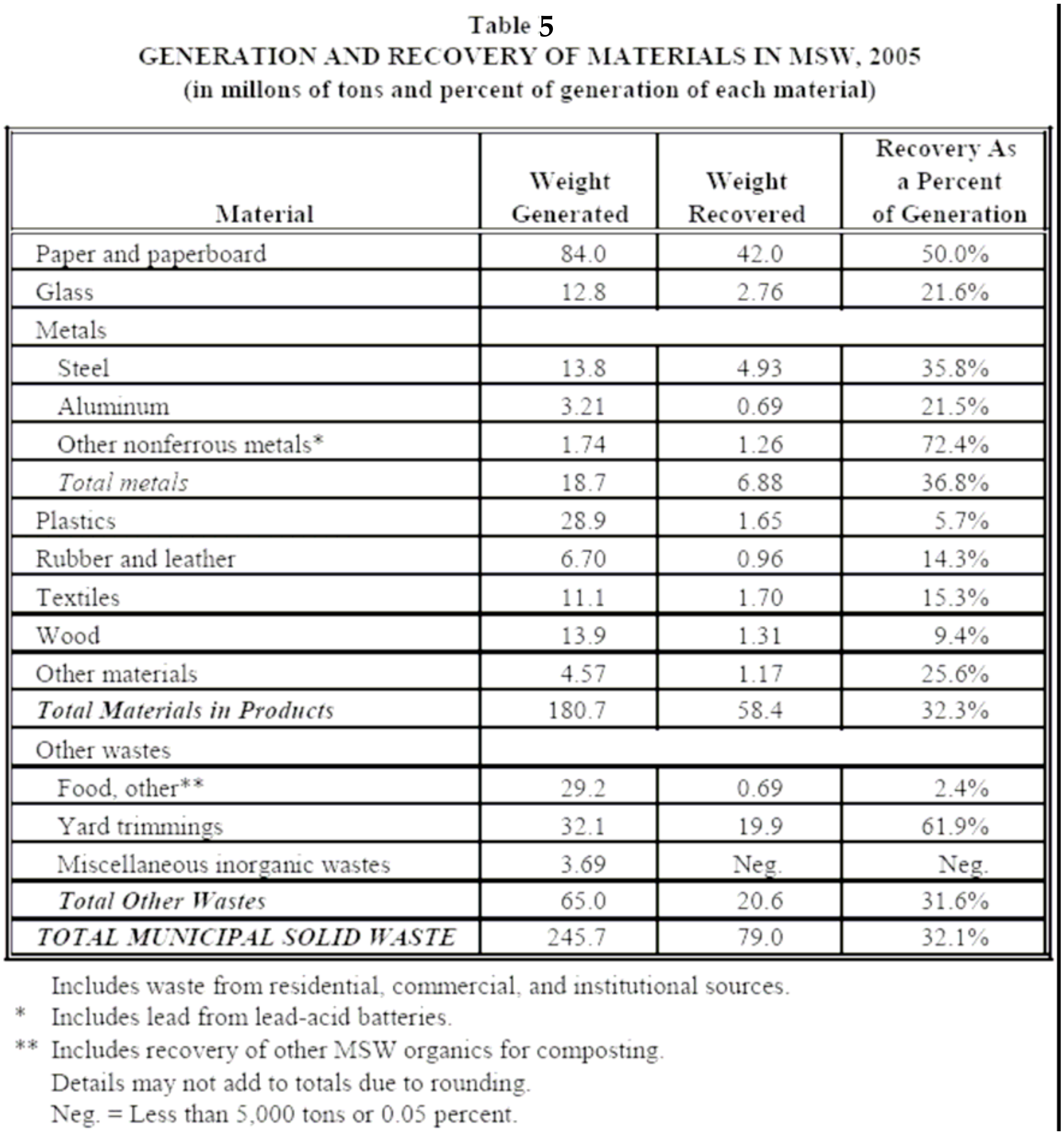


Table 5
GENERATION AND RECOVERY OF MATERIALS IN MSW, 2005
(in millons of tons and percent of generation of each material)

Material	Weight Generated	Weight Recovered	Recovery As a Percent of Generation
Paper and paperboard	84.0	42.0	50.0%
Glass	12.8	2.76	21.6%
Metals			
Steel	13.8	4.93	35.8%
Aluminum	3.21	0.69	21.5%
Other nonferrous metals*	1.74	1.26	72.4%
Total metals	18.7	6.88	36.8%
Plastics	28.9	1.65	5.7%
Rubber and leather	6.70	0.96	14.3%
Textiles	11.1	1.70	15.3%
Wood	13.9	1.31	9.4%
Other materials	4.57	1.17	25.6%
Total Materials in Products	180.7	58.4	32.3%
Other wastes			
Food, other**	29.2	0.69	2.4%
Yard trimmings	32.1	19.9	61.9%
Miscellaneous inorganic wastes	3.69	Neg.	Neg.
Total Other Wastes	65.0	20.6	31.6%
TOTAL MUNICIPAL SOLID WASTE	245.7	79.0	32.1%

Includes waste from residential, commercial, and institutional sources.
* Includes lead from lead-acid batteries.
** Includes recovery of other MSW organics for composting.
Details may not add to totals due to rounding.
Neg. = Less than 5,000 tons or 0.05 percent.

Durable Goods (Wood)

After wood hits the municipal solid waste stream, only a negligible percentage (as a percent of generation) is recovered (EPA 2006).

Nondurable Goods (Paper and Paperboard)

About 42.4 percent of paper and paperboard is recovered from the municipal solid waste stream (EPA 2006). Newspapers constitute the largest portion of this recovery, with 88.9 percent of newspapers generated being recovered for recycling. An estimated 62.6 percent of high-grade office papers and 38.5 percent of magazines is recovered. And the recovery percentages are increasing in recent years. Recovery percentage of "Other Commercial Printing" is about 10.4 percent; standard mail is recovered at an estimated 35.8 percent, and directories at an estimated 18.2 percent.

Containers and Packaging

Paper and paperboard containers and packaging is recovered at a rate of 58.8 percent; corrugated containers accounted for most of that amount (EPA 2006). Approximately 15 percent of wood packaging (mostly wood pallets removed from service) is recovered for recycling.

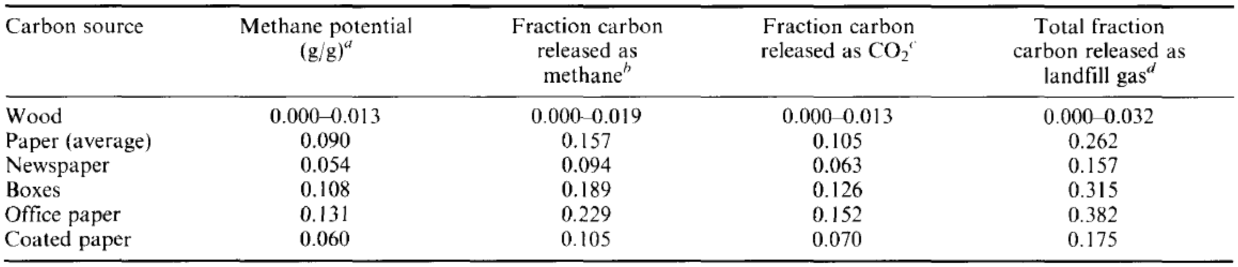
Carbon in Forest Products Disposed in Landfills

Percent of carbon released from paper as landfill gases = 26 percent, on average, over a 5-40 year period (Micales and Skog 1997).

Percent of carbon released from wood as landfill gases = 0-3 percent, over a 5-40 year period (Micales and Skog 1997).

Micales and Skog (1997) give additional decomposition rates for wood products in landfills, shown in Table 6.

Table 6. Estimate of the maximum production of carbon in paper and wood that is converted to methane and carbon dioxide in landfills (Micales and Skog 1997)



Carbon source	Methane potential (g/g)[a]	Fraction carbon released as methane[b]	Fraction carbon released as CO_2[c]	Total fraction carbon released as landfill gas[d]
Wood	0.000–0.013	0.000–0.019	0.000–0.013	0.000–0.032
Paper (average)	0.090	0.157	0.105	0.262
Newspaper	0.054	0.094	0.063	0.157
Boxes	0.108	0.189	0.126	0.315
Office paper	0.131	0.229	0.152	0.382
Coated paper	0.060	0.105	0.070	0.175

Fossil Fuel Displaced by Forest Products

Replacing fossil fuels with sustainably-produced biomass will reduce the net flow of CO_2 (and other greenhouse gases) to the atmosphere. Gustavsson and others (1995) express the efficiency of this substitution in reduced emissions per unit of used land or biomass. Energy inputs into biomass production and conversion are biomass-based, resulting in a CO_2-neutral fuel cycle, while CO_2 emissions from fossil fuels are estimated for the complete fuel cycles. Substituting biomass for fossil fuels in electricity and heat production is prevalent in California's forest products industry and provides important CO_2 reductions per unit of biomass.

There is no net production of CO_2 from wood combustion because biomass energy is produced in a controlled, closed environment (Morris 2007).

Each ton of biomass burned to generate electricity prevents the emission of 0.4 ton of carbon dioxide (CO_2) into the atmosphere from natural gas-fired power plants (California Biomass Collaborative June 2005).

The DOE Technical Guidelines provide methods for estimating the effects of substituting biomass energy for fossil-fuel energy. Calculating the release of carbon from the combustion of biomass fuel and the displacement of emissions from fossil fuels is described in the Technical Guidelines for the electricity supply sector (DOE 2006).

The Oak Ridge National Laboratory compiled the following reference list of conversion factors used in bioenergy applications; the list can be accessed at: http://bioenergy.ornl.gov/papers/misc/energy_conv.html.

Energy Units—Quantities

- 1.0 joule (J) = one Newton applied over a distance of one meter (= 1 kg m^2/s^2).
- 1.0 joule = 0.239 calories (cal)
- 1.0 calorie = 4.187 J
- 1.0 gigajoule (GJ) = 10^9 joules = 0.948 million Btu = 239 million calories = 278 kWh
- 1.0 British thermal unit (Btu) = 1055 joules (1.055 kJ)
- 1.0 Quad = One quadrillion Btu (10^{15} Btu) = 1.055 exajoules (EJ), or approximately 172 million barrels of oil equivalent (boe)
- 1000 Btu/lb = 2.33 gigajoules per tonne (GJ/t)
- 1000 Btu/US gallon = 0.279 megajoules per liter (MJ/l)

Energy Units—Power

- 1.0 watt = 1.0 joule/second = 3.413 Btu/hr
- 1.0 kilowatt (kW) = 3413 Btu/hr = 1.341 horsepower
- 1.0 kilowatt-hour (kWh) = 3.6 MJ = 3413 Btu
- 1.0 horsepower (hp) = 550 foot-pounds per second = 2545 Btu per hour = 745.7 watts = 0.746 kW

Energy Units—Energy Costs

- \$1.00 per million Btu = \$0.948/GJ
- \$1.00/GJ = \$1.055 per million Btu

Some Common Units of Measure

- 1.0 U.S. ton (short ton) = 2000 pounds
- 1.0 imperial ton (long ton or shipping ton) = 2240 pounds
- 1.0 metric tonne (tonne) = 1000 kilograms = 2205 pounds
- 1.0 US gallon = 3.79 liter = 0.833 Imperial gallon
- 1.0 imperial gallon = 4.55 liter = 1.20 US gallon
- 1.0 liter = 0.264 US gallon = 0.220 imperial gallon
- 1.0 US bushel = 0.0352 m^3 = 0.97 UK bushel = 56 lb, 25 kg (corn or sorghum) = 60 lb, 27 kg (wheat or soybeans) = 40 lb, 18 kg (barley)

Areas and Crop Yields

- 1.0 hectare = 10,000 m^2 (an area 100 m x 100 m, or 328 x 328 ft) = 2.47 acres
- 1.0 km^2 = 100 hectares = 247 acres
- 1.0 acre = 0.405 hectares
- 1.0 US ton/acre = 2.24 t/ha
- 1 metric tonne/hectare = 0.446 ton/acre
- 100 g/m^2 = 1.0 tonne/hectare = 892 lb/acre

For example, a "target" bioenergy crop yield might be: 5.0 US tons/acre (10,000 lb/acre) = 11.2 tonnes/hectare (1120 g/m^2)

Biomass Energy

- **Cord:** a stack of wood comprising 128 cubic feet (3.62 m^3); standard dimensions are 4 x 4 x 8 feet, including air space and bark. One cord contains approximately 1.2 U.S. tons (oven-dry) = 2,400 pounds = 1,089 kg
    - 1.0 metric tonne **wood** = 1.4 cubic meters (solid wood, not stacked)
    - Energy content of **wood fuel** (HHV, bone dry) = 18-22 GJ/t (7,600-9,600 Btu/lb)
    - Energy content of **wood fuel** (air dry, 20% moisture) = about 15 GJ/t (6,400 Btu/lb)
- Energy content of **agricultural residues** (range due to moisture content) = 10-17 GJ/t (4,300-7,300 Btu/lb)
- Metric tonne **charcoal** = 30 GJ (= 12,800 Btu/lb) (but usually derived from 6-12 t air-dry wood, i.e. 90-180 GJ original energy content)
- Metric tonne **ethanol** = 7.94 petroleum barrels = 1,262 liters
    - Ethanol energy content (LHV) = 11,500 Btu/lb = 75,700 Btu/gallon = 26.7 GJ/t = 21.1 MJ/liter. HHV for ethanol = 84,000 Btu/gallon = 89 MJ/gallon = 23.4 MJ/liter
    - Ethanol density (average) = 0.79 g/ml (= metric tonnes/m^3)
- Metric tonne **biodiesel** = 37.8 GJ (33.3 - 35.7 MJ/liter)
    - biodiesel density (average) = 0.88 g/ml (= metric tonnes/m^3)

Fossil Fuels

- **Barrel of oil** equivalent (boe) = approx. 6.1 GJ (5.8 million Btu), equivalent to 1,700 kWh. "Petroleum barrel" is a liquid measure equal to 42 U.S. gallons (35 Imperial gallons or 159 liters); about 7.2 barrels oil are equivalent to one tonne of oil (metric) = 42-45 GJ.
- **Gasoline:** US gallon = 115,000 Btu = 121 MJ = 32 MJ/liter (LHV). HHV = 125,000 Btu/gallon = 132 MJ/gallon = 35 MJ/liter
    - Metric tonne gasoline = 8.53 barrels = 1356 liter = 43.5 GJ/t (LHV); 47.3 GJ/t (HHV)
    - Gasoline density (average) = 0.73 g/ml (= metric tonnes/m^3)
- **Petro-diesel** = 130,500 Btu/gallon (36.4 MJ/liter or 42.8 GJ/t)
    - Petro-diesel density (average) = 0.84 g/ml (= metric tonnes/m^3)
- Note that the energy content (heating value) of petroleum products per unit mass is fairly constant, but their density differs significantly—hence the energy content of a liter, gallon, etc. varies between gasoline, diesel, kerosene.
- Metric tonne **coal** = 27-30 GJ (bituminous/anthracite); 15-19 GJ (lignite/sub-bituminous) (the above ranges are equivalent to 11,500-13,000 Btu/lb and 6,500-8,200 Btu/lb).
    - Note that the energy content (heating value) per unit mass varies greatly between different "ranks" of coal. "Typical" coal (rank not specified) usually means bituminous coal, the most common fuel for power plants (27 GJ/t).
- **Natural gas:** HHV = 1027 Btu/ft3 = 38.3 MJ/m^3; LHV = 930 Btu/ft3 = 34.6 MJ/m^3
    - Therm (used for natural gas, methane) = 100,000 Btu (= 105.5 MJ)

Carbon Content of Fossil Fuels and Bioenergy Feedstocks

- **coal** (average) = 25.4 metric tonnes carbon per terajoule (TJ)
    - 1.0 metric tonne **coal** = 746 kg carbon
- **oil** (average) = 19.9 metric tonnes carbon / TJ
- 1.0 US gallon **gasoline** (0.833 Imperial gallon, 3.79 liter) = 2.42 kg carbon
- 1.0 US gallon **diesel/fuel oil** (0.833 Imperial gallon, 3.79 liter) = 2.77 kg carbon
- **natural gas (methane)** = 14.4 metric tonnes carbon / TJ
- 1.0 cubic meter **natural gas (methane)** = 0.49 kg carbon
- carbon content of **bioenergy feedstocks:** approx. 50% for woody crops or wood waste; approx. 45% for graminaceous (grass) crops or agricultural residues

Conclusions

Increasing the productivity of California's forestlands through greater investments in forest management could lead to significant gains in reducing atmospheric carbon. Carbon life cycle analysis has shown that, while actions on the part of a forest landowner to intensify forestry practices may lead to less carbon stored in the forests, they create positive carbon leakage through greater use of wood products in the market place. The leakage is positive because it reduces carbon emissions to the atmosphere. The effect of producing and using more wood products reduces consumption of more fossil fuel-intensive products. Importantly for carbon accounting, the project boundary for carbon and wood flows extends beyond the perimeter of the forest area whenever wood is harvested for products.

Attempts to increase carbon storage in forests via prohibitions on harvesting can: reduce the net benefits of carbon sequestration by the forest sector; reduce the availability of wood fiber for the forest value chain and for biomass fuels; increase the risk of loss of stored carbon via fire or infestation; and increase the costs of forest products, causing them to lose market share to competing products that do not store carbon and are more energy and carbon intensive.

We can increase sequestration to the stock of carbon in forest products and landfills (without increasing the aggregate consumption of wood and paper products) by: increasing product use life; increasing product recycling; and shifting product mix to a greater proportion of lignin-containing solid wood, paper, and paperboard products, which decay less in landfills (Skog and Nicholson 2000).

The positive and significant contributions of actively managed forests and their products have important policy implications for carbon accounting and reporting. We need to provide technical assistance and incentives to landowners who already manage forests sustainably to add carbon sequestration and storage as a management goal. Any incentive to manage forest lands to produce a greater amount of forest products would likely increase the share of lands positively contributing to a reduction of carbon dioxide in the atmosphere. Forest management for wood fiber provides a critical economic incentive for keeping land in forests rather than being converted to uses providing no climate and energy benefits. Also, we need uniform and equitable forest policies and protocols that provide the means of determining additionality, inventory, permanence, verification, leakage, and adequately account for the role of forest products in meeting societal needs from paper to long-term structures and recycling (Helms 2007a).

The carbon removed from the atmosphere and sequestered in forest products throughout their useful lives should be more fully recognized, as should the carbon and energy attributes of forest products compared to competing products.

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