Carbon and Carbon Dioxide Equivalent Sequestration in Urban Forest Products

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Executive Summary

An important function of trees and forests both in and out of urban areas is carbon sequestration. Nowak and Crane (2002) have estimated that urban trees in the U.S. hold about 774 million tons of carbon; this is approximately 2.84 billion tons of CO_2e (equivalent). Forest product research has demonstrated that over their usable lives wood products continue to store carbon (C), reducing the build-up of atmospheric CO_2. This area of research has focused on products manufactured from hardwood and softwood trees harvested only from rural timberlands. There has been no comparable research on the sequestration potential of wood products made from urban trees.

The purpose of this report is to estimate within several different scenarios the net cumulative total amounts of CO_2e that could be sequestrated in urban hardwood products. The three products investigated are landscape mulch (chips), biomass for fuel (chips) and solid wood products.

Chips used for landscape mulch have many benefits including moisture conservation, aesthetics, and soil enrichment. However, from a CO_2e sequestration perspective, landscape chips should be classified as a short-term product (lifetime of 5 years or less). Consequently, we conclude that chips used for landscape purposes (ground cover) have zero long-term CO_2e sequestration.

Chips used as a biomass fuel source for heat and/or power were evaluated from a fossil fuel displacement (substitution) perspective. Using an LCA-type approach for both urban trees and coal (by calculating CO_2e emissions from harvesting or mining through combustion), we found the following: 1 ton of urban wood at 50 percent moisture content displaces approximately 0.41 tons of coal and results in approximately 0.92 tons of avoided fossil fuel emissions (CO_2e). From a national perspective, combusting 10 percent of the annual urban tree removals (at 50 percent moisture content) in place of coal results in avoided fossil fuel emissions of roughly 2.1 million tons. This is the equivalent of about 1% of annual energy-related CO_2e emissions attributable to coal; the value is also comparable to annually removing over 367,000 passenger cars from U.S. highways.

The solid wood product portion of this study (making up the majority of this report) focuses only on hardwood products made from urban trees and excludes both paper products and all products made from urban softwoods.

The argument is made that urban wood should be judged not only by existing commercial standards but in addition by the unique characteristics of urban trees themselves. The appeal of products made from urban hardwoods are provenance; history; unusual figure, color, and dimensions; and personal and community meaning. These attributes could be the components of an urban hardwood standard.

The argument is also made that the only CO_2e emissions specifically attributable to the production of urban hardwood products are those that arise primarily from kiln-drying. Other emissions arising from felling, chipping and transportation, would have occurred regardless of whether the trees were disposed of as green waste or used as chips for fuel and landscaping.

An Excel spreadsheet model was created to generate net cumulative CO_2e estimates for urban forest hardwood products over a 30-year period. Projections in the model are based on assumptions about the growth rate in the capacity of the nation's urban forests to sequester C and on the potential sequestration amount of C that could end up in urban hardwood products. For comparison, a baseline scenario was developed consisting of 0% growth in sequestration capacity, an annual removal rate for urban trees of 1%, and a 10% utilization rate of removed trees to make solid hardwood products. This baseline (minimum) scenario resulted in over 124 million tons of CO_2e being withheld from the atmosphere by the end of 30 years.

By increasing the size of the urban forest (increasing sequestration capacity) by 1% and 2%, and holding the utilization rate constant at 0.1% (1% removals at 10% utilization), the cumulative net CO_2e sequestration increases to 139 and 157 million tons, respectively. A 1% increase raises sequestration by 12% over the baseline while the 2% increase raises sequestration by 27%.

When the size of the urban forest sequestration capacity is held constant but the utilization rate (sequestration potential) is increased above the baseline to 0.2% and 0.3%, the cumulative net CO_2e sequestration in urban forest products over 30 years jumps to 248 and 372 million tons, respectively. Using an optimistic 2% sequestration growth and 0.3% utilization rate, urban forest hardwood products would withhold almost 472 million tons of CO_2e from the atmosphere in thirty years.

We also examined estimated growth capacity and utilization in two regions of the U.S. (North East and West). We found that strong nationwide growth in urban hardwood product sequestration over three decades is possible even when growth does not occur in all or a majority of regions.

From this study, forest products manufactured from felled urban trees have significant CO_2e sequestration benefits with conservative estimates between 124 and 472 million tons over a 30-year period. And, although urban tree chips used for landscape purposes have no long-term carbon storage benefits, chips combusted for heat and/or power have the potential to annually displace 2.1 million tons of fossil fuel emissions. Thus, a practice of diverting urban hardwoods to solid products and utilizing other urban tree material as an alternative to fossil fuels would contribute to the reduction of CO_2 in the earth's atmosphere and move our nation closer to making the highest and best use of felled urban trees.

The Economic Benefits of Urban Trees

The prevailing view of urban trees and the nation's urban forests is that their economic value is almost entirely derived from the functions they perform while standing and alive. These functions range from aesthetic appeal that adds market value to residential neighborhoods to shade and wind blocks that reduce building energy costs to moderating the amount of storm water runoff that leads to erosion and pollution of urban streams and rivers.

A prevailing view, but a changing one, is that urban trees lose nearly all of their value when they come down and become mainly a costly waste removal problem. The residual market value of these trees comes from their being processed into mulch and fuel, a default use that bypasses their potential greater value as a source of wood for solid wood products.

Carbon and Carbon Dioxide Equivalent Sequestration

A very important function of trees and forests both in and out of urban areas is that by sequestering carbon, C, they withhold an even larger amount of CO_2 e (equivalent) from the earth's atmosphere. At present, the body of credible climate research identifies CO_2 as a major green house gas that as it accumulates in the earth's atmosphere contributes to global warming. Nowak and Crane (2002) have estimated that urban trees in the U.S. hold about 774 million tons of C, thus withholding 2.84 billion tons of CO_2 from the atmosphere. The prevailing view is that this function is performed by standing and live trees. While attention has been devoted to changes in the level of sequestration as a function of changes in the size of the nation's urban forests, no attention has been devoted to the sequestration consequences of what becomes of the downed trees themselves.

However, forest product research has amply demonstrated that wood products continue to sequester carbon and an even greater amount of CO_2e over their usable lives (Heath *et al*., 1996, Ingerson, 2009, Tonn and Marlin, 2006). This area of research has focused on products (including paper) manufactured from hardwood and softwood trees harvested only from rural timberlands.

There has been no comparable research on the sequestration potential of wood products made from urban trees. Yet, if wood products from commercially harvested forests can sequester carbon, so can the same products made from urban trees. Hence, some proportion of the existing 774 million tons of carbon sequestered in urban trees can also be sequestered in urban forest products. As pointed out by Smith *et al.* (2006):

> *Failing to account for carbon in wood products significantly overestimates emissions to the atmosphere in the year in which the harvest occurs.*

Though the reference is to rural timber products, the statement applies equally, if not more so, to urban forest products as well.

The purpose of this report is to estimate within several different scenarios the annual amounts of CO_2e sequestration over a three decade span as the urban forest products industry forms and grows. The three products investigated are landscape mulch (chips), biomass for fuel (chips) and solid wood products. Landscape mulch is considered a short-term forest product and is discussed in Appendix E. Biomass for fuel is analyzed in Appendix F from the perspective as a displacement for fossil fuel energy (coal). CO_2e sequestration of solid wood products comprise the majority of this report.

Our research focuses only on solid hardwood products made from urban trees and excludes both paper products and all products made from urban softwoods. For western states such as California, excluding urban softwood products is an important omission that should be addressed in future research. Excluding urban paper products may be an important omission as well. Not including either means that CO_2e sequestration remains underestimated for the near-term future covered by this report.

Estimates of forest products sequestration are possible because the forest products industry is large, well-established, and has been producing products for a very long time. The industry has been around long enough to generate adequate data for such estimates and to encourage research on this subject.

By contrast, the urban forest products industry is just emerging. The idea of using downed urban trees as a source of merchantable logs goes back to the mid-nineties (Cesa and Lempicki, 1994). Since then there has been persistent but sporadic growth in the number of urban forest products businesses, starting mainly in California. The formation of this industry is only now beginning to accelerate and take shape across the nation. Growth is also the result of efforts to create an Urban Forest Products Alliance and to hold state urban forest products conferences in California and North Carolina in 2011.

Unlike the long-established forest products industry, estimates for urban forest hardwood products in this report are projections based on assumptions about the growth of this industry over the coming 30 years, not on where it is at present. An Excel spreadsheet model was created to estimate the net CO_2e sequestration in urban solid hardwood products based on assumptions about the capacity of the nation's urban forest to sequester C and on the potential amount that could be sequestered in urban hardwood products. The latter is used as the estimate of industry growth. In addition, as discussed below in greater detail, CO_2 emissions generated by kiln drying urban hardwoods are subtracted from CO_2e sequestration estimates to arrive at net equivalent sequestration in (short) tons.

While in principle, sequestration in solid hardwood forest products and solid urban forest hardwood products should work the same way, in practice, the difference between harvesting rural timberlands and reclaiming fallen hardwoods from urban forests are very different activities driven by different forces underwritten by perceptions of urban forests based on decades of commercial forestry practices. To understand how urban forest products can sequester CO_2e, the differences between rural and urban hardwood timber harvesting must be made explicit and the latter must be seen as separate and distinct from the former. This requires the emerging urban forest products industry in the U.S. to be seen as an industry with its own identity and its own standard for judging the potential value of urban trees as a source of wood for hardwood products.

Commercial Grading Standards and Sequestration

Nowhere is the difference between the two more apparent than in the use of the hardwood lumber grading standard to judge whether urban hardwoods are acceptable for wood products. The National Hardwood Lumber Association (NHLA) was established just before the turn of the twentieth century to create a uniform hardwood grading standard. Though the standard has undergone changes since then, from an economic perspective its purpose then and now is to create a fungible product that can be purchased sight unseen in large quantities by intermediate and end users. By this standard, much of the wood from urban trees would have little or no market value because it would be graded below #3 common and thereby be deemed unacceptable by hardwood buyers. Falling short means that much if not the majority of urban hardwood would be judged unsuitable for solid wood products, leaving mulch and fuel as the usual default product alternatives.

In short, imposing the established hardwood grading standard on urban forest wood limits its sequestration potential, and the estimates of this potential, by limiting its use as a source for solid wood products.

An Urban Hardwood Standard

Broader acceptance of urban hardwoods as suitable for wood products requires an additional standard that recognizes the uniqueness and related market values of urban hardwoods, market values in some cases that are greater on a per board foot basis than lumber of the same species graded as FAS. In this report, we do not offer a fully developed urban hardwood standard but do offer five unique characteristics of urban hardwoods that could eventually form the basis for such a standard. In the meantime, including these characteristics does extend the acceptability of urban hardwoods beyond, perhaps even well beyond, the NHLA standard alone.

Judging urban hardwoods by their unique characteristics and evaluating them by the NHLA grading standards are so different as to be polar opposites. Commercial standards exist to enable buyers to purchase lumber by the tractor-trailer load (usually about 10,000 board feet). Buyers would never consider inspecting every board in a truck load of lumber (unless there is a dispute between buyer and seller. Then a professional grader would be hired to inspect the lumber). Such a task would be impossible for buyers and with a fungible product, not necessary.

By contrast, judged by their unique characteristics urban hardwoods would not be fungible. To the contrary, urban trees would be judged by the total usable wood they yield. This standard extends beyond just standardized lumber sawn from logs to include limbs, burls, and other parts of a tree trunk not sawn into lumber but shaped nevertheless into products by hand and power tools. Hence, in this report, urban wood refers to both lumber sawn from urban trees and wood not sawn but used to make products.

The basic difference between these two different ways of judging urban hardwoods arises from the different narratives that describe the origin and significance and respective market values of commercially traded lumber versus urban hardwood product wood from urban trees.

Lumber from the commercial timber and lumber manufacturing process has little or no distinctive and engaging narrative, no stories that describe its provenance, history and no recognition of unique figure, grain, color, dimensions or the personal or community meaning. For wholesale and retail buyers, commercial lumber's only story is that it is a homogeneous product that has at best a vague origin and no history or meaning beyond its utility as a commodity input to the production of final wood products. This is slightly less so for certified lumber based on chain-of-custody certification that partially bridges the narrative divide between the origin of the lumber and the retail wood product it becomes. Still, certification is less of a narrative and more of an assurance to buyers who are concerned that the trees from which the wood came were harvested in a sustainable manner.

By contrast, the unique characteristics of urban hardwoods are provenance, history, appearance, dimensions and meaning. One or a combination of these attributes comprises the distinct narrative of urban timber used to make solid wood products, including pallets, skids, and shipping containers as well. The examples below focus on furniture, crafts, and products such as flooring and cabinets used in residential and commercial buildings.

Provenance

Provenance refers to the origin or recognizable place where urban trees stood. As examples, this can range from a cucumber magnolia that stood on the Biltmore Estate in Asheville, NC (See Photos 1, 2 and 3) to ash trees felled by the Emerald Ash Borer that stood on public property in Wilmette, IL. In marketing, these products can be branded by their provenance. Being able to explicitly identify the origin of the wood gives it additional market value, especially now at a time when buyers increasingly insist on knowing the origins of the products they buy.

Photos 1, 2, and 3: A cucumber magnolia was planted in 1900, by George and Edith Vanderbilt to commemorate the birth of their daughter, Cornelia, the same year. Known as the "baby tree", it stood until 2008 when it finally had to be removed. As shown above, the main trunk was cut into three saw logs and removed by crane. The logs were sawn into slabs that were used to make, among other pieces of furniture, a conference table now in use at the Biltmore Estate in Asheville, NC.

History

History simply means the tree or trees have historical significance that adds market value when branded by that history. A prominent example is the tulip poplar that stood for centuries on the grounds of St. John's College in Annapolis, MD (Photos 4 and 5). It was the last standing Liberty Tree from the Revolutionary War. These trees were used as rallying places by American colonists and both Loyalists and the British destroyed the trees wherever they found them. However, the one in Annapolis survived. The tree was fatally damaged by a hurricane in September, 1999, and was taken down a month later. Most of the wood was rescued from the chipper and landfill and was eventually purchased by Taylor Guitars who used the wood to make a limited series of Liberty Tree guitars.

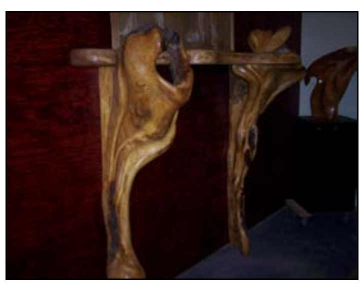
Figure, Color, Dimensions

Uniformity of grain and color in commercial lumber are highly desirable because this establishes the fungibility of the product for large volume buyers. Highly figured boards, those streaked with unusual color, or not sawn to uniform widths or lengths, or that are sawn into slabs (above 8/4") are unacceptable under commercial grading standards but are often perfect for unique products. One of the most prominent examples is found in the furniture of the late George Nakashima who used slabs, often of walnut from around New Hope, PA, to make unique tables (Photos 6 and 7). Much of his work consisted of highly figured and often bookmatched boards with live (natural) edges that frequently contained prominent cracks that he bridged with butterfly keys, a signature design element for which his pieces are widely known. Much of the lumber he used and that his daughter, Mira, now uses would be rejected by commercial hardwood grading standards.

The very idea of lumber is based on logs processed through a sawmill. However, the wood from limbs and roots of urban trees that bypass a mill are useful as illustrated in the sculptured work of the late John Metzer. These pieces were made with a chainsaw, angle grinder, hand chisels and sanders (Photos 8 and 9). These pieces, too, will sequester C as long as they exist.


Photos 4 and 5: Wood from the last standing Liberty Tree on the grounds of St. John's College was rescued from the landfill and eventually used to make a limited series of acoustic guitars honoring the historical importance of the tree.


Photos 6 and 7: The large single slab on the left was sawn from a very large walnut tree and then air dried. The table top on the right consists of two book matched slabs of cucumber magnolia from the Biltmore Estate.




Photos 8 and 9: Pieces of an urban tree that would have otherwise been discarded or chipped were transformed into sculptured pieces of art by the late John Metzler owner of Urban Tree Forge, an urban forest products company in Pittsburgh, PA.

Personal Meaning

As they become familiar with the idea, urban property owners who lose trees that have personal value are learning that they can have those trees transformed into furniture, flooring, or other building materials for their own use, thus retaining some of the sentiment invested in the trees themselves. As a personal example, one of the authors of this report (Sherrill) made about two-dozen pieces of furniture from a 500 year-old bur oak for an Ohio family that since the mid-nineteenth century owned the property where the tree stood (Photos 9, 10, 11 and 12).

Photos 9, 10, 11, and 12: The first photograph above left, circa 1890, is of the owner of the farm where a giant bur oak stood. His descendants still own the farm property. In the mid-nineties the oak was felled by a windstorm. At that time the tree was estimated to be 500 years old. The large limbs were sawn into lumber and used to make the table and rocking horse shown above, as well as more than a dozen other pieces for family members.

Community Meaning

Like individual property owners, communities often form attachments to trees in public places as well. When these trees come down, they too can be used to make furniture for public use such as benches below**.**

Photo 13: These benches were made from oak (left) and Osage orange (right) trees removed from a Cincinnati, OH park. Design students at the University of Cincinnati designed and built both benches that were then placed back in city parks.

The Commercial and Urban Hardwood Standards

The set of characteristics listed above are an addition to and not a replacement for the NHLA standard. Nothing prevents both from being used in a complementary way and nothing prevents tractor-trailer loads of urban lumber (from large land clearing operations, for example) from being graded by commercial standards and sold in these quantities. Together these two ways of judging urban hardwoods could raise the urban wood recovery factor.

Even so, commercially graded and marketed urban lumber has a general narrative that distinguishes it from its commercially harvested counterpart. Unlike the latter, urban lumber has the additional attribute of being reclaimed or post-consumption material that would otherwise either be treated as waste or used as fuel or mulch, neither of which sequesters C other than for very short time periods. Being able to reclaim urban wood for different but nevertheless socially, environmentally, and economically valuable uses has growing appeal to architects, builders and property owners alike. There is reason to believe that in the coming years, urban wood judged both ways will be increasingly incorporated into building standards such as LEED and called for in construction, furniture making, wood crafts and pallet manufacturing. With this additional attribute and priced about the same as commercial lumber, the level of demand for urban lumber can be expected to rise significantly over the near future as the building industry recovers.

In summary, wood from urban trees used in applications from furniture and crafts to building materials or pallets, and whether judged by the NHLA standard or their unique characteristics, all should be counted as urban wood products that have the potential to sequester carbon. Using established grading standards and some kind of new standard that recognizes unique features means a larger proportion of downed urban trees can be counted as having carbon sequestration potential than would be the case by using the commercial standard alone.

Commercial Timber Harvesting Versus Harvesting Urban Timber

Harvesting Urban Timber CO_2 Emissions

In several important ways, harvesting urban trees is the opposite of commercial logging in the nation's forests. In urban areas, we have to wait until natural forces such as wind, disease, infestation, or age fell trees. They also come down owing to human actions such as land clearing for development, because they pose a public hazard, or they damage hardscape or utility lines and pipes. None of these human actions are in any way related to logging. Urban trees are not harvested for their saw log, fuel, or other commercial content as are trees in traditionally logged forests. This is an important point because it bears directly on the emission side of CO_2e sequestration and what those emissions are attributable to.

All emissions associated with commercial logging must be attributed to the logging process itself, from those linked to sky lines to feller bunchers, skidders, tractor-trailers, chainsaws, debris pile burning and clearing and replanting. The machines and the CO_2 they emit are used for the sole purpose of commercial logging: if no logging, no use of machinery, then no emissions.

There are CO_2 emissions associated with planting and maintenance of urban trees, especially those on public property and right-of-ways. In addition, urban trees felled by natural causes or by human actions, unless left on-site, are removed by a process that requires felling, limbing, bucking, and quite often, chipping. Both maintenance and removal must be done regardless of what becomes of the trees themselves, whether they are disposed of as green waste in a landfill or are converted to fuel or mulch. This means that the emissions from both are not properly attributable to their subsequent use as a source of material for urban forest products since maintenance and removal would have occurred anyway. In short, there are no marginal emissions attributable specifically to the use of downed urban wood as a source of material for urban forest products.

Unlike commercial logging, diverting urban trees to make products does not enlarge the carbon footprint of felling those trees beyond what was created by the basic removal process itself. But, the subsequent sawing of urban logs into lumber does generate emissions because the band saws used in urban areas are powered by fossil fueled engines. And, additional emissions are generated when a portable mill is towed to the site where the trees were felled. The question is whether the sum of these emissions are greater than what would be required to reduce logs on-site to shorter lengths for ease of loading and hauling or for chipping and then the chipping itself. When used as mulch and fuel, urban trees must be processed one or more times through chippers and tub grinders so that they are reduced to chips of a usable size. All of these machines are driven by fossil fueled engines as well and all emit significant quantities of CO_2. In this report, we assume that the emissions attributable to sawing are no more, and possibly even less, than those from chippers and grinders.

We also make an equivalent assumption about emissions generated by hauling: whether to a mill, a landfill, or the tree service company's property; no one destination accounts for more than any other. The marginal emissions attributable to hauling to sawmills are assumed to be zero.

We also recognize that each of these assumptions is open to question and may warrant additional research.

Kiln Drying

When trees are processed for use as urban hardwood products, kiln drying may be required for the proportion of the wood that is not air-dried. Kiln drying is unique to producing usable wood for most though not all urban wood products. Hence, we cannot assume that kiln drying is offset by some equivalent process when the wood is used as mulch or fuel. In general, kilns for use in drying urban wood are small and powered by electric motors used to drive fans and dehumidification units. Because the electricity largely is generated by the nation's fossil fuel plants, emissions from drying must be factored into the estimation of net CO_2e sequestration. Drying requires a significant amount of energy and is a major proportion of the CO_2 emitted in the production of lumber for urban hardwood products. Energy consumption also varies widely depending on species, equipment and method of drying. In particular, electrical consumption depends on the type of kiln and whether pre-dryers are used and whether the lumber is air-dried before being kiln-dried (Bergman and Bowe, 2008).

At present during the formative growth of the urban forest products industry, the proportions of urban wood that will be air-dried versus kiln dried are difficult to discern. And, as the industry expands, these proportions may shift from whatever they are now.

Informal and limited case study examination of small urban forest products businesses across the U.S. reveals a variety of approaches to drying. Those who produce lumber for more traditional indoor products, from flooring to furniture, tend to dry their lumber in dehumidification kilns to avoid subsequent air-drying defects as well as insect and fungal infestation in the finished products. But then some rely on air-drying entirely for indoor products. One author of this report (Sherrill) makes the majority of his commissioned pieces from air-dried lumber. More time is required for the lumber to reach indoor EMC but there are no drying and transportation costs (or related emissions) and one result, especially for walnut, is often superior color of the finished pieces. Bowl turners turn wet wood into rough shapes, allow them to air dry, and then finish the dried pieces. Some indoor wood art is air dried for a time and then shaped into final pieces for indoor use with the understanding that some checking may subsequently appear as the wood continues to dry. This appears to be acceptable for large indoor pieces such as mantels and structural beams. In these cases, checking is considered as an acceptable design element of products made from a living material.

A small but very promising niche in the urban forest products industry is indicated by the growing demand for slabs, basically large single or book-matched boards with live edges that range from 8/4 to 32/4 thickness, that have been air-dried. These unique pieces are highly prized (and priced) because of their size and the extended drying time required, typically 4 to 6 years and beyond. One business in northern California specializes in slabs air-dried on average for about 6 years (yielding in one case a conference table top made from a single slab 20 feet long, about 5 feet wide, and 32/4 thick). Wood for outdoor products is air dried down to the approximate outdoor EMC. In one case, the business uses wet wood to make small outdoor structures allowing for shrinkage in construction. In another business, the wood for outdoor structures is kiln-dried first.

Even so, emissions from kiln drying (if employed) are directly and solely attributable to the production of urban hardwood products. Kiln drying is not required when urban hardwood is used as either fuel or mulch. Estimates of kiln drying emissions are built into the Excel model and are subtracted from the CO_2e sequestration estimates to arrive at cumulative net CO_2e sequestration amounts. Based on evidence among urban forest product companies the authors are familiar with, we assume that 80% of urban hardwood is kiln-dried, a percentage that may be on the high side of reality.

Omitted is electric power generated by sawmills themselves from wood residue they produce. Some might argue that sawmill generated electricity is carbon neutral while others would disagree. We will not enter that debate here other than to say that, at present, unlike large commercial sawmills, small urban forest products businesses are not likely to generate their own electric power given the current practice of using stainless steel shipping containers and readily available dehumidification units described below to build low cost kilns that are relatively inexpensive to operate using power from the nation's power grid.

Based on innovative efforts of Eric Oldar, California Forestry and Fire Protection (CALFIRE), the most widely used approach to kiln drying urban wood among small urban forest products businesses is to use standard 20 foot or 40 foot stainless steel shipping containers matched to an appropriate dehumidification unit (including fans and temperature and humidity controller) that will dry up to 2,000 board feet (20 foot container) or 4,000 board feet (40 foot container) in one charge. For small businesses, the cost of building such a kiln is modest even by small business standards. A 40 foot used stainless steel container sells for about $3,000, the dehumidification unit, controller, and fans for about $8,000, and material for tracks for loading and unloading lumber about $1,000. Wiring done by a licensed electrician (parts and labor) costs about $3,000. For about $15,000 total, an operating kiln can be built. The dehumidification unit operates on 220 volts, single phase, and therefore requires no special higher voltage lines than what is ordinarily found in homes or commercial buildings. Though electric rates vary across the nation, these kilns fully-charged can run continuously for about $100 to $200 per month. There is the added advantage that small urban forest products businesses can start with one unit and add duplicates as their businesses grow.

Photos 14 and 15: The 20 foot shipping container kiln above is on permanent loan from California Forestry and Fire Protection to Palomar Community College's Cabinet and Furniture Technology Program in San Marcos, CA.

Urban Forest Hardwood Product Life

Though difficult to quantify because of their uniqueness, the proportion of some urban wood products may have longer lives than those estimated for similar products made from commercially harvested timber. Much of the furniture, crafts, and wood art made from urban trees are one-of-a-kind products, often commissioned, that acquire the status of heirlooms or art that will likely be held for very long periods of time, unlike equivalent pieces made from commercial lumber that are more likely to be discarded sooner. The longer the urban wood pieces last, the longer they sequester C. Arguably, these products will last as long, possibly longer, than the very urban trees they were made from. On the other hand, products such as flooring and trim integrated into building construction would last no longer than the buildings themselves unless they are then recycled.

Overall, as long as urban forests are not logged for timber, the marginal emissions contribution of using urban wood as a source of material for solid wood products is zero. The marginal emissions would rise above zero only when urban forests were harvested for their saw log content; that is, like their commercial counterpart, only when CO_2 emitting machines are used for the purpose of logging.

While logging urban forests is extremely unlikely, the idea that urban trees planted on public property could be selected and maintained with their end-of-life saw log value in mind has been proposed. The argument is that if local governments are going to bear the costs of planting and maintaining public trees anyway then why not select those trees, all other things equal, that will be most valuable when they finally come down.   Some portion of maintenance and removal CO_2 emissions would then have to be allocated to the trees subsequent use as source material for urban forest products since a factor in selection and maintenance is end value. At present, even this seems unlikely.

Estimating CO_2e Sequestration in Urban Forest Hardwood Products

Updating the work of Birdsey (1996), Smith *et al.* (2006) created look-up tables for forest and harvested carbon stocks that include estimates of the proportions of carbon stored in trees that end up sequestered in primary hardwood products in use. The estimates start with the proportion sequestered in the first year and then follow the diminishing proportions for the next 100 years. The proportions diminish as the products from the first year go progressively out of use in subsequent years. Smith *et al.* also provide estimates for six different regions defined by states that together cover the lower 48 states and the District of Columbia. The first 30 of the 100 year estimates used in this report are given in Appendix A.

In addition to their single estimate of carbon sequestered in all urban areas in the lower 48 states, Nowak and Crane (2002) also provide estimates by state. State-by-state sequestration estimates were allocated among the six regions used by Smith *et al*. (see Appendix B). The sum is the amount sequestered in urban areas in the 48 states plus the District of Columbia. The Nowak and Crane estimates are for urban hardwoods and softwoods.

In turn, the Smith *et al.* estimates of proportions of carbon in hardwood products in use can be applied to the six regions to calculate the amount of carbon sequestered in products in each region and in total for the U.S.

Also factored into this model are adjustments for above ground use only of urban trees (this eliminates roots as a source material) and the amount of above ground wood usable for urban hardwood products. The exact values and roles of each in the computational model are shown in the equation in Appendix C.

In the Excel model, sequestration estimates vary as a function of changes in the following two variables:

1. the capacity of the nation's urban forests to sequester carbon (measured by urban forest size); and[1]
2. the potential proportion of CO_2e in the nation's urban forests that could be captured in hardwood products made by the urban forest products industry (measured by utilization rate).

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[1] Over time capacity can vary as a function of urban forest size as measured by the number of trees for a given area based on net tree replacement, by changes in the mix of species that sequester differing amounts of carbon, or by the weighted average age of the trees that comprise the forest, or some combination of any two or more of these. For a discussion of factors that affect the spatial variability of urban forests, see Dwyer, John F. *et al.* (2000) Connecting People with Ecosystems in the 21st Century: An Assessment of Our Nation's Urban Forests. USDA Forest Service. General Technical Report, PNW-GTR-490, chapter 3. In addition, urban forests can grow by annexing rural forestland at the periphery of expanding urban areas. Nowak, David J. and Walton, Jeffrey T. (2005) estimate that by 2050 urban forests will have taken over about 45 thousand square miles of rural forests, an area they point out that is about the size of the State of Pennsylvania. How capacity varies is a very important issue, especially for estimates that stretch decades into the future where number of trees, urban forest acreage, species mix, and average age can vary significantly. However, in this report no attempt is made to identify how each of these variables contribute independently or collectively to changes in sequestration capacity.

The Excel computational model is used here to generate cumulative net CO_2e sequestration estimates for a thirty-year period. These estimates are based on three annual growth rates -- 1%, 2%, and 3% -- in urban forest CO_2e sequestration capacity and on three percentages – 0.1%, 0.2%, and 0.3% -- of the CO_2e that has the potential to be sequestered annually in urban hardwood products. To be clear, this variable is not a measure of urban trees harvested annually either by number or in board feet. Rather, it is the potential proportion of CO_2e in the nation's urban forests that could be captured in hardwood products made by the urban forest products industry. As such, this second variable is also treated as an indirect or proxy measure of the potential growth rate in the industry: higher percentages would mean that the industry is making more intensive use of urban hardwoods to make products that sequester more CO_2e. While arguments could be made for different percentages for both of these variables, either lower or higher, we started with these which we consider to be conservative. Different percentages can be easily entered into the model.

Tables 1 through 5 provide five different growth scenarios:

1. growth in urban forest sequestration capacity and no growth in (utilization rate) potential product sequestration (thus, no growth in the urban forest products industry itself),
2. no growth in urban forest sequestration capacity but growth in potential product sequestration (hence, growth in the industry),
3. growth in both sequestration capacity and potential product sequestration,
4. partial growth in both but in just two regions of the country, and
5. no growth in urban forest sequestration capacity but 3% annual growth in potential product sequestration.

Each of these five illustrates the net sequestration potential of urban hardwood forest products under different assumptions about where utilization growth originates and the rate at which it increases. The Excel model will accommodate any variations on the numbers used to generate these five illustrations.

Table 1 below provides estimates of the net cumulative CO_2e sequestration after 30 years based on three growth rates for capacity: a baseline of 0%; and 1% and 2%. Potential sequestration is fixed at 0.1% (10% utilization of the 1% annually removed). **The baseline for comparisons is 124.1 million tons of CO_2e based on 0% capacity growth (no change in size of urban forest over a 30 year period) and 0.1% potential annual sequestration.** (For comparison purposes, this baseline is highlighted in **bold** in each table below).

Growth in product sequestration arising only from growth in urban forest capacity represents a minimum growth in the urban forest industry's efforts to convert fallen urban hardwood trees into carbon sequestering products. Here the industry has not grown more than what is required to absorb potential capacity that comes from growth in the urban forest itself. But even with no additional industry growth and assuming that it keeps pace with the growth of the nation's urban forests, the industry at its initial size could produce enough hardwood products at 1% urban forest capacity growth to increase cumulative net CO_2e sequestration by 12.2% over 30 years, from the baseline amount of about 124.1 million tons to 139.3 million tons. At 2% capacity growth, cumulative net CO_2e sequestration would increase by 26.7% over 30 years.

Table 1. Net Cumulative CO_2e Sequestration in Urban Hardwood Products for 30 Years with Fixed Potential Sequestration Rate

Change in C Sequestration Capacity of Urban Forest (Change in size of urban forest)	Potential Annual Sequestration Rate (10% use of 1% annual removal)	Net Cumulative CO_2e Sequestration in Urban Hardwood Products
0.0%	**0.1%**	**124.1 million tons**
1.0%	0.1%	139.3 million tons
2.0%	0.1%	157.2 million tons

In Table 2, net cumulative sequestration is estimated using three different potential sequestration percentages: the baseline of 0.1%; and then 0.2%, and 0.3% on 0% growth in urban forest sequestration capacity. With fixed capacity, this represents growth in product sequestration that arises from the growth of the urban forest products industry and rising output of hardwood products that sequester CO_2e. That is, the industry has launched and is making increasingly intensive use of trees from a fixed resource base. At 0.2% annual growth rate, net CO_2e sequestration by the end of the 30 year period has doubled from the baseline amount of 124.1 million tons to 248.1 million tons. And, at 0.3% net CO_2e sequestration has tripled to 372.2 million tons.

Table 2. Net Cumulative CO_2e Sequestration in Urban Hardwood Products for 30 Years with Sequestration Capacity Fixed at 0% Annual Growth Rate

Change in C Sequestration Capacity of Urban Forest (Change in size of urban forest)	Potential Annual Sequestration Rate (Utilization rate over 30 years)	Net Cumulative CO_2e Sequestration in Urban Hardwood Products
0.0%	**0.1%**	**124.1 million tons**
0.0%	0.2%	248.1 million tons
0.0%	0.3%	372.2 million tons

In Table 3, the two lowest growth rates for capacity and potential – 1% and 0.2%, respectively -- are combined to estimate cumulative net CO_2e sequestration. In what might be seen as the entry into the best of all possible worlds for sequestration (at least within the constraints of this model), over a 30 year span the urban forest yields more usable hardwood trees for carbon sequestering products and the urban forest industry is utilizing these trees at a higher annual rate. Both the resource base and the industry are growing modestly. At a 1% annual growth rate for capacity and a 0.2% growth rate for potential sequestration, the cumulative net sequestration after 30 years is just under 278.7 million tons, an increase of 125% above the baseline of 124.1 million tons.

Table 3. Net Cumulative CO_2e Sequestration in Urban Hardwood Products for 30 Years with Sequestration Capacity of 1% and 2% and Potential Sequestration Rates 0.2% and 0.3%

Change in C Sequestration Capacity of Urban Forest (Change in size of urban forest)	Potential Annual Sequestration Rate (Utilization rate over 30 years)	Net Cumulative CO_2e Sequestration in Urban Hardwood Products
0.0%	**0.1%**	**124.1 million tons**
1.0%	0.2%	278.7 million tons
2.0%	0.3%	471.6 million tons

Table 3 provides further entry in the best of all worlds with an annual growth in capacity of 2% and potential sequestration of 0.3%. At the end of three decades, total cumulative net CO_2e sequestration has reached just over 471.6 million tons, almost four times the baseline amount of 124.1 million tons.

Table 4 provides estimates based on growth in two of the six regions, the North East and the West. At a 2% increase in capacity and a 0.3% increase in potential sequestration in just these two regions, nationwide cumulative net sequestration increased to 255.6 million tons. Compared to the baseline, total net sequestration for the U.S. more than doubled from 124.1 million tons to 255.6 million tons. This illustrates that relatively strong nationwide growth in urban hardwood product sequestration over three decades is possible even when growth does not occur in all or even a majority of regions.

Table 4. Net Cumulative CO_2e Sequestration in Urban Hardwood Products for 30 Years with Sequestration Capacity of 2% and Potential Sequestration Rates 0.3% for Two of Six Regions

Change in C Sequestration Capacity of Urban Forest (Change in size of urban forest)	Potential Annual Sequestration Rate (Utilization rate over 30 years)	Net Cumulative CO_2e Sequestration in Urban Hardwood Products
0.0%	**0.1%**	**124.1 million tons**
2.0%	0.3%	255.6 million tons

Finally, in Table 5, the result of the much more optimistic assumption that while the nation's urban forest sequestration capacity does not grow at all, sequestration potential, and by implication the urban forest products industry, reaches 3% annually matching the nation's long run average GDP growth rate. Cumulative net sequestration at the end of thirty years would reach about 3.7 billion tons, or about 30 times the baseline amount of 124.1 million tons.

Table 5. Net Cumulative CO_2e Sequestration in Urban Hardwood Products for 30 Years with Sequestration Capacity Fixed at 0% and Potential Sequestration Rates of 3%

Change in C Sequestration Capacity of Urban Forest (Change in size of urban forest)	Potential Annual Sequestration Rate (Utilization rate over 30 years)	Net Cumulative CO_2e Sequestration in Urban Hardwood Products
0.0%	**0.1%**	**124.1 million tons**
0.0%	3.0%	3,721.7 million tons

Summary

By expanding the standard used to judge the acceptability of urban hardwoods to include the five characteristics that distinguish urban wood from its commercially harvested counterpart, we have expanded the resource base for urban hardwood product output. An expanded base means that the potential for CO_2e sequestration is greater as well, perhaps even much greater, than would be under just the NHLA grading standard alone. What remains to be explored is the exact quantitative link between an expanded view of grading standards and the quantity of urban trees used in the future as the urban forest products industry grows.

From this study, forest products manufactured from felled urban trees have significant CO_2e sequestration benefits. Conservative estimates ranging from 124 (baseline scenario)[2] to 472 million tons of sequestrated CO_2e over a 30-year period are realistic and achievable in the next three decades, even with modest increases in urban forest capacity (size) and sequestration potential (utilization rate). And, although urban tree chips used for landscape purposes have no long-term carbon storage benefits (Appendix E), chips combusted for heat and/or power have the potential to annually displace 2.1 million tons of fossil fuel emissions (Appendix F). Thus, a practice of diverting urban hardwoods to solid products and utilizing other urban tree material as an alternative to fossil fuels would contribute to the reduction of CO_2 in the earth's atmosphere and move our nation closer to making the highest and best use of urban trees.

[2] The estimate of 124 million tons of CO_2e is quite conservative and well below the average annual growth rate of the U.S. GDP.

APPENDIX A. Average Proportions of Carbon Sequestered in Hardwood Products In-Use by Region For a Thirty Year Period

Year	North East	South East	North Central	South Central	West	Pacific West
0	0.614	0.609	0.585	0.587	0.568	0.531
1	0.572	0.565	0.544	0.543	0.529	0.481
2	0.534	0.526	0.507	0.503	0.494	0.438
3	0.500	0.491	0.473	0.468	0.464	0.400
4	0.469	0.459	0.443	0.437	0.437	0.367
5	0.440	0.431	0.416	0.409	0.412	0.338
6	0.415	0.405	0.391	0.383	0.390	0.312
7	0.391	0.381	0.368	0.360	0.369	0.289
8	0.369	0.359	0.347	0.338	0.350	0.268
9	0.349	0.339	0.328	0.319	0.332	0.248
10	0.331	0.321	0.310	0.301	0.316	0.231
11	0.317	0.307	0.296	0.288	0.304	0.220
12	0.303	0.293	0.283	0.275	0.292	0.208
13	0.289	0.279	0.269	0.261	0.280	0.197
14	0.275	0.252	0.256	0.248	0.268	0.185
15	0.260	0.243	0.242	0.235	0.256	0.174
16	0.250	0.234	0.233	0.226	0.248	0.168
17	0.224	0.225	0.224	0.218	0.240	0.162
18	0.230	0.216	0.215	0.209	0.233	0.155
19	0.220	0.207	0.206	0.201	0.225	0.149
20	0.212	0.201	0.197	0.192	0.217	0.143
21	0.205	0.195	0.191	0.186	0.211	0.139
22	0.198	0.189	0.185	0.180	0.205	0.135
23	0.191	0.183	0.179	0.174	0.200	0.130
24	0.184	0.175	0.172	0.168	0.194	0.126
25	0.178	0.170	0.165	0.162	0.188	0.122
26	0.173	0.165	0.160	0.158	0.183	0.119
27	0.168	0.160	0.155	0.153	0.179	0.116
28	0.163	0.155	0.150	0.149	0.174	0.113
29	0.152	0.150	0.145	0.144	0.170	0.110

Smith, James E. *et al.* (2005). Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States. USDA Forest Service, North Eastern Research Station, General Technical Report NE-343. Taken from Table 6.

APPENDIX B. Carbon Sequestered in Urban Areas by States and Regions

Regions/States	Carbon Storage (short tons)	States	Carbon Storage (short tons)
North East			
Connecticut	9,060,700	New York	27,099,600
Delaware	2,666,400	Ohio	38,670,500
Maine	14,011,800	Pennsylvania	29,272,100
Maryland	18,462,400	Rhode Island	838,200
Massachusetts	17,744,100	Vermont	1,523,500
New Hampshire	8,383,100	Washington, DC	526,000*
New Jersey	29,133,500	West Virginia	4,662,900
Subtotal	202,054,800		
South East			
Florida	34,461,900	South Carolina	17,737,500
Georgia	46,916,100	Virginia	31,856,000
North Carolina	28,019,200		
Subtotal	158,990,700		
North Central			
Illinois	31,427,000	Missouri	17,606,600
Indiana	15,873,000	Nebraska	2,278,100
Iowa	10,601,800	North Dakota	363,000
Kansas	5,371,000	South Dakota	1,205,600
Michigan	22,646,800	Wisconsin	11,983,400
Minnesota	25,781,800		
Subtotal	145,138,400		
South Central			
Alabama	41,622,900	Mississippi	13,216,500
Arkansas	8,737,300	Oklahoma	11,715,000
Kentucky	11,466,400	Tennessee	32,973,600
Louisiana	13,834,700	Texas	28,389,900
Subtotal	161,956,300		
West			
Arizona	10,692,000	Nevada	3,218,600
California	30,331,400	New Mexico	1,130,800
Colorado	5,747,500	Utah	3,670,700
Idaho	2,515,700	Wyoming	291,500
Montana	21,940,600		
Subtotal	79,538,800		
Pacific West			
Oregon	7,052,100		
Washington	19,415,000		
Subtotal	26,467,100		
Total US	**774,146,100**		

Combined Sources: Smith, James E. *et al.* Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forests Types of the United States. General Technical Report NE-343, Table 1, p. 2. Nowak, David J. & Daniel E. Crane. Carbon storage and sequestration by urban tress in the USA. (2002). 116, Table 3, p. 386. Excluded from the Nowak *et al.* estimates are 492 square kilometers plus the District of Columbia.

*The District of Columbia was separately added back in from Nowak, David J. *et al.* Washington, DC's Urban Forest. (2006). Forest Service. Resource Bulletin NRS-1.

APPENDIX C. Sequestration and Emissions Estimation Methods

The Excel model used for the sequestration estimates by region is summarized in the equation below. [3] Eight factors comprise the model:

1. carbon sequestered in urban forests by region (constant),
2. growth in sequestration capacity of urban forest (variable),
3. proportion that could be sequestered in urban hardwood products (variable),
4. proportion of above ground mass of urban trees (constant),
5. above ground mass usable for urban hardwood products (constant),
6. proportion of above ground mass estimated to be actually used in producing hardwood products (constant),
7. CO_2 equivalent (e) for every unit of C (constant), and
8. CO_2 emissions attributable to drying (varies according to values of urban forest sequestration growth and/or growth in proportion actually used in producing urban hardwood products).

$$\mathbf{TNS_R} = \left(\left(\left(\left(\left(\sum_{t=0}^{t=29} (Q_{t-1} \times p_{t+1})\right) + (Q_t \times p_{t=0})\right) \times .74\right) \times .50\right) \times 3.67\right) - E_t$$

Where $\mathbf{TNS_R}$ = Total Net CO_2e Sequestration by Region in urban hardwood products for year **t**

- **t=0** = year 0;
- **t=29** = the 30th or last year;
- **t** = current year;
- **t-1** = year before current year **t**;
- **t+1** = year after year 0;
- **Qt** = quantity C sequestered in current year **t** (total regional amount sequestered times the proportion, 0.1% , 0.2%, or 0.3% yields what is potentially available);
- **p** = proportion of hardwood products in use and sequestering C;
- $\mathbf{E_t}$ = emissions generated by kiln drying urban wood using fossil fuel grid electricity in year **t**;
- **.74** = above ground level biomass available for use (i.e., exclusion of roots)
- **.50** = amount of above ground biomass usable for the production of urban hardwood products including but not limited to saw logs; and,
- **3.67**. = units of CO_2e (equivalent) for every unit of C.

Assuming 0% growth in the sequestration capacity of the North East Region urban forests and a 0.1% potential sequestration (factor 3 in the above list), the computational steps for the first two years are as follows (these separate steps are compressed into just a few column formulas in the Excel model):

1. 202,054,800 tons C sequestered in North East Urban forests x 0.001, potential sequestration in urban hardwood products = 202,055 tons;

[3] The "starting point" for sequestration calculations begins with urban forest carbon sequestration estimates from Nowak and Crane (2002) and includes Smith *et al.* (2006) estimates for products made from industrial roundwood (hardwood saw logs).

2. 202,055 tons x .74, above ground biomass available for use = 149,521 potential tons sequestered in products;

3. 149,521 tons x .50 above ground mass usable for hardwood products = 74,760 tons;

4. 74,760 tons x .614 actual C sequestered in first year (0) products = 45,903 tons;

5. 45,903 tons x 3.67 CO_2e/C = 168,463 CO_2e tons sequestered in urban hardwood products;

6. **168,463 CO_2e tons - 29,401 CO_2** emissions attributable to kiln drying = **139,602 CO_2e** total net tons sequestered in urban hardwood products in the first year (0);

7. for the second year (1) the calculations are the same as they are for the first year except that the first year's above ground mass usable for hardwood products, 74,760 tons, must now be multiplied by .572, first year C sequestered reduced for loss of products from the first year: the result in the second year is 42,763 tons C actually sequestered in first year products;

8. 42,763 tons from the first year + 45,903 tons from the second year = 88,666 cumulative tons sequestered;

9. 88,666 cumulative C tons sequestered x 3.67 CO_2/C = 325,403 CO_2e tons sequestered in urban hardwood products; and,

10. **325,403 CO_2e** tons sequestered **– 58,802 CO_2** emissions attributable to kiln drying = **266,601 CO_2e** total cumulative net tons sequestered in urban hardwood products at the end of the second year.

This same computational process repeats through the 30th year bringing the cumulative net sequestration of CO_2e in urban hardwood products to about 34.3 million tons at the end of the three decade period for the North East Region.

Basically, the calculations start with C sequestered in urban forests and end with CO_2e sequestration minus CO_2 drying emissions in urban forest hardwood products. The derivation of the factors used are described in Appendix D.

The equation above applies separately to each region. The following equation sums sequestration in urban hardwood forest products for all six regions.

$$\mathbf{TNS_{US} = \sum_{n=1}^{n=6} (TNS_R)_n}$$

Where **TNS_{US} =** Total Net CO_2 Sequestration for the 6 districts (all 48 states plus the District of Columbia) at the end of 30 years. For example, from Table 1 above, **TNS_{US} = 124.1 million tons**.

The sequestration part of the model is based on following four assumptions:

1. The Smith *et al*. in-use estimates (**p** in the region equation above) are provided for years 0 through 10 and thereafter at five year intervals. To calculate the missing proportions within the five year intervals, the difference between the last year before a given interval and the

last year of the interval is divided by 5 and then in sequence are subtracted from each year within the interval (this adjustment is not reflected in the equation but is in the spreadsheet data). For example, from Table 1, the 10th year proportion for the North East is .331 and the 15th is .260. The difference, .071, divided by five is .014. This is subtracted from .331 leaving .317. The same .014 is then subtracted then from .317 leaving .303. This proceeds until the 15th year leaving .260. This procedure is followed for the missing years in each of the intervals for all six regions. This is simply a way to bridge the gaps in the data so that there is a declining proportion for each of the years 11 through 14, 16 through 19, and so on.

2. Even though the in-use estimates are for products made from rural not urban hardwoods they are applied to urban products here because they are the only multi-year estimates available. Other single estimates of hardwood waste from the production are much higher and the corresponding in-use proportions much lower: Wood Waste and Furniture Emissions Task Force (1998) estimated the furniture yield from raw lumber at 45%. For states in part of the North East and north central regions used in this report, Bergman and Bowe (2008) estimate that 45.8% of hardwood log volume ends up as dried and planed lumber. Ingerson (2010) estimates that as little as 18% of the original live tree may actually end up in wood products while also acknowledging that estimates of any kind are scarce. Lower rates suggest that sequestration is lower as well, though there is no direct way to determine how much lower. The qualitative argument made here is that the addition of the urban hardwood standard described earlier in this report results in more urban wood being used, and more sequestration, than would be the case when only commercial grading standards are used. Hence, we will use the Smith *et al.* estimates until better ones appear.

3. The first year begins with no prior accumulation of C in urban hardwood forest products.

4. We do not account for the possible emissions that might arise from the disposal of urban hardwood products over the 30 year period. In effect, we assume disposal does not lead to further emissions (for example, discarded products end up in landfills).

The emissions, $\mathbf{E_t}$, calculations start with annual C sequestration in urban forest hardwood products and end with CO_2 attributable to kiln drying. Estimates by region are summarized in the following equation:

$$\mathbf{E_t = ((((A_t \times 2{,}000) \div 18.689) \times 23.49) \times .637) \times .80) \div 2{,}000}$$

Where $\mathbf{A_t}$ = actual annual C sequestered in urban forest hardwood products in tons (step #4 in sequestration computations above) in year **t**;

2,000 = pounds/ton;

18.689 = pounds of C/ft^3 based on an average hardwood density of 37.378 pounds/ft^3 multiplied by .50 (C proportion of tree);

23.49 = CO_2 pounds/ ft^3 attributable to kiln drying using electricity from fossil fueled power plants;

0.637 = proportion of total electricity produced in North East region by fossil fuel power plants (see Appendix D for proportions for all six regions;

0.80 = proportion of total urban hardwood products kiln dried; and,

2,000 = pounds back to tons conversion for subtraction from CO_2e in tons sequestered in hardwood products.

This equation converts the estimated weight of C sequestered in urban forest hardwood products to the cubic feet of products to the weight of the CO_2 emissions attributable to kiln drying. The latter is then subtracted from CO_2e sequestration to arrive at net sequestration estimates. A description and derivation of factors are also given in Appendix D.

This part of the model rests on two assumptions: CO_2 accumulates year after year in the atmosphere without reductions (Bergman and Bowe, 2008) of the kind equivalent to the downward adjustments in hardwood product sequestration from year to year; and, 80% of urban hardwoods are kiln dried.

Using the first year in the North East Region as an example and assuming 0% growth in the sequestration capacity and 0.1% potential sequestration, the separate computational steps for the first two years are as follows (as with the gross sequestration estimates above, these separate steps are compressed into just a few column formula's in the Excel model):

1. 202,054,800 tons C sequestered in North East Urban forests x 0.001, potential sequestration in urban hardwood products = 202,055 tons;

2. 202,055 tons x .74, above ground biomass available for use = 149,521 potential tons sequestered in products;

3. 149,521 tons x .50 above ground mass usable for hardwood products = 74,760 tons;

4. 74,760 tons x .614 actual C sequestered in first year (0) products = 45,903 tons;

5. 45,903 tons x 2,000 pounds/ton = 91,806,000 C pounds;

6. 91,806,000 ÷ 18.689 pounds of C sequestered in 1 ft^3 of dry hardwood = 4,912,301 ft^3 of dried urban forest hardwood products;

7. 4,912,301 ft^3 x 23.49 CO_2 pounds of emissions/ ft^3 attributable to kiln drying = 115,389,950 pounds of CO_2 emissions;

8. 115,389,950 pounds of CO_2 emissions x .637 the proportion of total electricity produced in North East region by fossil fuel = 73,503,398 pounds of CO_2 emissions;

9. 73,503,398 pounds x 0.80, proportion of kiln dried urban hardwood use in products = 58,802,718 pounds;

10. 58,802,718 pounds ÷ 2,000 pounds/tons = **29,401** tons CO_2 emissions attributable to kiln drying; and,

11. the calculation for the second year (1) is the same as the first except that the first year's CO_2 emissions are added to the second bringing the cumulative total for the second year to **58,802 tons**.

This same computational procedure is followed for the next 28 years for this region and for 30 years for each of the other five regions. For the North East, at the end of 30 years a total of 882,037 tons of CO_2 will have accumulated in the atmosphere. The total accumulation by the 30^{th} year for all six regions would be 3,328,951 tons. However, by the 30^{th} year net sequestration attributable to urban hardwood products will have reached 124.1 million tons.

APPENDIX D. Estimation Factors for CO_2e Sequestration and Kiln-Drying Emissions

The following are based on LCI results for total emissions per unit basis of planed dry lumber from incoming hardwood logs to planed dry lumber for north central and north eastern states (i.e., gate-to-gate).

LCI fossil and biomass CO_2 emissions = 139 and 428 kg/ m^3 planed dry hardwood lumber, respectively.*

Drying accounts for 25% of total consumption of electricity; therefore we assumed drying accounts for 25% of fossil fuel emissions. In addition, 80% of biomass fuel emissions are attributed to kiln drying.

.25 x 139 kg/m^3 = 34.8 kg CO_2/ m^3 + (428 biomass CO_2 kg/ m^3 x 80%) ** attributable to drying = 377.2 kg CO_2/ m^3.

377.2 kg CO_2/ m^3 = 829.8 lbs./35.32 ft^3 = 23.49 lbs. CO_2/ ft^3 attributable to kiln drying.

Average oven dried (OD) wood density for kiln dried American hardwood sawn lumber is 600 kg/ m^3.***

600 OD kg/ m^3 = 37.378 OD lbs./ ft^3. Since 50% of wood is carbon, .50 x 37.378 = 18.689 lbs. C/ft^3.

1 lb. of dry wood (0.5 kg C) is equivalent to 1.835 lbs. of atmospheric CO_2:
Atomic mass of carbon (C) is 12
Molar mass of CO_2: (C) 1x12 + (O_2) 2x16 = (CO_2) 44.
44/12 = 3.67 is the multiple by which 1 atom of C stored in the biomass of a tree reduces atmospheric CO_2.

Hence, 1 lb. of C x 3.67 (CO_2/C) = 3.67 lb. CO_2e removed from the atmosphere.

Estimates of emissions attributable to kiln drying using electric power from fossil fuel plants is derived from the U.S. Energy Information Agency's publication: *1990 - 2009 Net Generation by State by Type of Producer by Energy Source (EIA-906, EIA-920, and EIA-923)*. This is available from http://www.eia.gov/cneaf/electricity/epa/epa_sprdshts.html.

Data for 2009, the latest available at the time this report was written, was reorganized into the six regions. The total electricity generated by all fuel sources in each region was calculated as was the percentage of electricity generated by fossil fuel plants alone (by regulated utilities and independent generators). The six percentages for the six regions are used as reduction factors in the calculation of fossil CO_2 emissions attributable to kiln-drying. In the example used in the equation given in Appendix C, the percentage for the North East is 63.7%. For the other five regions the percentages are:

South East	65.4%	West	66.0%
North Central	64.1%	Pacific West	20.2%
South Central	72.4%		

* Bergman, Richard D. and Scott A. Bowe. (2008). Environmental Impact of Producing Hardwood Lumber using Life-Cycle Inventory. Wood and Fiber Science, 40(3), pp. 448-458.

**Comstock, G.L. (1975). Energy Requirements for Drying of Wood Products. In Wood Residues as an Energy Source. Forest Products Research Society. Madison, WI. pp. 8 – 12.

*** Oliver, Rupert. 2010. A Preliminary Assessment of the Carbon Footprint of American Hardwood Kiln Dried Lumber Supplied to Distributors in the European Union. Forest Industries Intelligence Ltd.

APPENDIX E. Using Urban Tree Chips for Landscape Mulch

One of the tangible products of urban tree removal is landscape mulch. In a typical scenario, trees, or portions thereof, are removed from an urban property, and fed directly into a chipper that breaks the woody material down into small pieces (chips). A typical sight on many streets and urban spaces is a tree crew worker feeding branches, tree tops and small trunks into a machine that is producing and blowing wood chips into a trailer. In some instances, the tree service firm will "donate" the chips to a homeowner, neighbor or community willing to accept the product. Some municipalities have public "wood chip sites" where tree service firms dump the chips for use by residents and public resource managers. In these instances, the chips are typically spread on the ground—for new plantings, around established tree and shrubs, as a surface for trails, etc. Ultimately, urban tree chips used in this manner serve as an inexpensive landscape mulch.

Another scenario is where a tree service firm produces and markets its own chip products as an income producing venture. Many firms in this category use "colorizing equipment" to "paint" the chips into various hues and shades such as brown, black, gold, and red. This landscape mulch product is often sold in bulk through nurseries and garden centers.

A third producer of landscape mulch from urban tree chips can be described as the large "aggregator". These firms often operate compost and organic recycling centers and obtain much of their raw material from tree service firms, land clearers, and homeowners. Mulch and related products such as potting soil and erosion control products are a primary focus of these firms. Colorizing equipment and bagging machines are often found at these businesses (including large tub grinders and other wood re-processing equipment). Mulch products are sold to a range of customers including big box stores, landscape supply stores, garden centers, tree nurseries, homeowners, and others.

Carbon Storage

Carbon is stored in forest products for various lengths of time. The half-life is one method to calculate carbon storage in various wood products. The U.S. Department of Energy has published a table that estimates the half-life for wood products by end use.[4] New residential construction of single-family homes is given an estimated half-life of 100 years, with household furniture pegged at 30 years, pallets at 6 years, and paper products at 2.6 years. Data is not provided for landscape chips although one can assume the half-life would be much closer to paper and pallets than furniture or residential construction.

Some studies have categorized wood chips, sawdust, bark and shavings as short-term forest products with an assumed decay rate of 10 percent per year.[5] Urban forest researchers have noted that trees converted to mulch "…will most likely release their carbon relatively soon after

[4] See chapter 7, p. 156 at: http://www.eforester.org/publications/jof/jof_cctf.pdf.

[5] See Winjum et al. 1998 and Harmon and Sexton 1996 research reports as cited in: http://soilslab.cfr.washington.edu/publications/Perez-Garcia.pdf.

removal".[6] Even if urban tree chips are equated to what is referred to as "fine woody debris" in a natural forest setting, sequestration rates are essentially zero.[7] Also, homeowners, landscapers, and other users of chips for landscape mulch recognize that repeated mulch applications are required as chips readily decompose in a 2-5 year time period.

Research in the area of composting with municipal yard trimmings (brush, yard waste, and leaf feed stocks) makes a strong case that compost renews and restores soils that have been depleted of organic content, thereby restoring soil organic carbon to higher levels. Composting research also argues that benefits include a reduced use of pesticides and fertilizers on lawns, gardens, green (open) spaces and golf courses.[8] Though results of this type of research appear promising, it is beyond the scope of this project to do an in-depth analysis of composting with wood chips.

Bottom Line

Tree chips used for landscape mulch are a sizable product manufactured from the urban forest. The benefits are numerous including conservation of moisture, erosion control, soil amendment, and aesthetics. However, for purposes of this project, landscape mulch produced from urban tree chips is assumed to have zero long-term carbon storage.

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[6] Nowak, D. and Crane, D. 2002. Carbon storage and sequestration by urban trees in the USA. Environmental Pollution, 116:381-389.

[7] See Woodall 2010. http://www.nrs.fs.fed.us/pubs/jrnl/2010/nrs_2010_woodall_002.pdf.

[8] See "Municipal Yard Trimmings Composting Benefit Cost Analysis", BioCycle July 2009, Vol. 50, No. 7, p. 21. http://www.jgpress.com/archives/_free/001903.html.

APPENDIX F. Using Urban Trees as a Fossil Fuel Displacement Strategy

In addition to sequestering carbon in solid wood products, combusting urban trees can offset fossil fuels like coal, natural gas, gasoline, diesel oil and fuel oil. Offsets (displacements) are one method of analyzing the impact of different fuels on greenhouse gas emissions to the atmosphere. The description below compares burning urban trees versus coal as an energy source for power (electricity) generation.[9] Specifically, carbon dioxide (CO_2e) emissions (equivalencies) for both urban wood and coal burning are evaluated on a micro (Table 1) and macro (Table 2) level.

Micro Level

Table 1 presents data on burning wood at various moisture contents in comparison to tons of coal displaced and avoided fossil fuel emissions (in pounds and tons). Note that burning one ton of wood (urban trees) at 50 percent moisture content (MC) is equivalent to displacing almost one ton of coal CO_2e emissions.

Table 1. Urban Wood vs. Coal – Displacement and Avoided Fossil Fuel Emissions

Urban Wood (tons) and Moisture Content (MC) (green basis)	Coal Displacement (tons) (approximate)	Avoided Fossil Fuel (CO_2e) Emissions (lbs) (1)	Avoided Fossil Fuel (CO_2e) Emissions (tons)
1 @ 50 % MC (2)	0.41 (3)	1844	0.92
1 @ 35 % MC (4)	0.54 (3)	2428	1.2
1 @ 20 % MC (5)	0.66 (3)	2968	1.5
1 @ Bone Dry (6)	0.83 (3)	3733	1.9

(1) Assumes coal @ 4497 lbs. CO_2 emissions/ton (includes mining, transportation and combustion)
(2) Assumes 8.5 MM BTUs/ton, green or "wet" basis and High Heat Value (HHV) (Source: Biomass Energy Data Book, 2010, Appendix A)
(3) Assumes 20.6 MM BTUs/ton, "wet basis" and HHV, for electric power sector (electricity-only and CHP); (Source: Biomass Energy Data Book, 2010, Appendix A); Calculations are as follows for 1 ton of wood at 50% mc: 8.5 mm btu/20.6 mm btu = 0.41; 0.41 x 4497 lbs. of CO_2 emissions = 1844 lbs.; 1844 lbs/2000 lbs. per ton = 0.92 ton of avoided CO_2e emissions.
(4) Assumes 11.05 MM BTU/ton (Source: Biomass Energy Data Book, 2010, Appendix A)
(5) Assumes 13.6 MM BTU/ton (Source: Biomass Energy Data Book, 2010, Appendix A)
(6) Assumes 17.0 MM BTUs/ton (Source: Biomass Energy Data Book, 2010, Appendix A)
Note: Table 1 compares wood versus coal on a High Heat Value basis (gross energy) although in a real-world situation, efficiencies for both fuels would not be 100%. An analysis conducted on a Low Heat Value basis (net calorific value) would lower the BTU outputs of both fuels but the overall results would be similar, i.e., one ton of wood at 50% moisture content (green basis) displaces approximately one ton of CO_2e emissions from coal (fossil fuel).

[9] The technologies for converting wood to energy include direct burning, hydrolysis and fermentation, pyrolysis, gasification, charcoal, and pellets and briquettes. The analysis described in this report does not delve into the details of any of these technologies although the comparison between urban wood and coal relates primarily to direct burning. Also, electrical power generation is relatively inefficient regarding energy "in" versus energy "out" regardless of the fuel source – wood or coal. The comparisons in Table 1 and Table 2 are not advocating that wood should be used for stand-alone power generation; rather, the comparisons highlight the impact of substituting wood for coal regarding fossil fuel emissions.

Table 1 is based on data computed from a (1) LCA study of coal-fired power plants and related reports, and (2) assumptions made in the main body of this report regarding urban tree use versus a "business as usual" scenario. Additional data and assumptions about coal and urban trees are given below.

Coal

In 2009, 94 percent of the coal combusted in the U.S. went to electric power (electricity only and combined heat and power—CHP).[10] Currently, coal supplies about 49 percent of all American electricity.[11]

A 1999 LCA found more than 93 percent of CO_2 emissions from coal power plants are attributed to 'combustion' with the remaining seven (7) percent or less attributed to mining, transportation (river) and construction.[12] The national average emission rate for coal combustion in the U.S. (EPA 2010)[13] is 203 lbs. of CO_2 per million BTU (British Thermal Unit); this is slightly less than a rate for electric utilities of about 208 lbs. of CO_2 per million BTU estimated in a 1994 report.[14] Also, the U.S. Department of Energy Biomass Energy Data Book, Edition 3, (2010) estimates the electric power sector heat content of coal (high heat value) at approximately 20.6 million BTUs per short ton.[15] Therefore, this report estimates the total CO_2 emissions from burning coal at a power plant (from mining to combustion) to be roughly 4497 lbs. per ton (see footnote for calculation).[16]

Urban Trees

The burning of urban trees (wood in general) emits approximately 220 lbs. of CO_2 per million BTU.[17] Urban tree removal and "disposal" follows steps that essentially will be replicated whether or not the woody residue is converted to energy or not. A "business as usual scenario" includes activities such as tree felling, limbing, chipping/grinding and transportation. The only extra step (if needed at all) to convert urban tree chips into "energy chips" is to re-grind the chips to make them "boiler-ready." In many instances, "energy chips" will have a reduced carbon footprint compared to landscape chips since many landscape products require additional grinding and shredding, the use of coloring equipment, bagging and handling activities, and increased transportation to move the

[10] Annual Energy Review 2010. http://www.eia.doe.gov/aer/pdf/aer.pdf.

[11] American Coal Council. http://www.americancoalcouncil.org/. (Accessed April 12, 2011).

[12] Spath, P., Mann, M., and Kerr, D. 1999. Life Cycle Assessment of Coal-fired Power Production. NREL/TP-570-25119. http://www.nrel.gov/docs/fy99osti/25119.pdf.

[13] EPA 2010. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008. Annex 2 (Methodology for estimating CO_2 emissions from fossil fuel combustion), Table A-32 and A-33. Available from section titled "Gallons of gasoline consumed": http://www.epa.gov/greenpower/pubs/calcmeth.htm. The value "203" was computed in the following manner: From Table A-32, carbon coefficient for coal equals 25.14 kg/mm Btu which is equivalent to 55.3 lbs./mm Btu (25.14 x 2.2 kg/lb); 55.3 x 44/12 = 55.3 x 3.67 = 203 lbs. CO_2e/mm Btu. [Note: 44/12 or 3.67 is the conversion factor from carbon (C) to carbon dioxide (CO_2)].

[14] Hong, B., and Slatick, E. 1994. Carbon Dioxide Emission Factors for Coal. U.S. Energy Information Administration. http://www.eia.doe.gov/cneaf/coal/quarterly/co2_article/co2.html.

[15] See Appendix A, Biomass Energy Data Book, http://cta.ornl.gov/bedb/index.shtml.

[16] 93% of emissions = (20.6 MM BTU/ton) x (203 lbs. CO_2/MM BTU) = 4182 lbs. CO_2 emissions/ton; since 93% of emissions = 4182 lbs. (see footnote 4), then 100% of emissions = 4497 lbs. CO_2/ ton (93/4182 = 100/X); also, 4497 lbs. CO_2/2000 lbs. per ton = 2.25 tons of CO_2 emissions per 1 ton of coal combusted.

[17] An Evaluation of Air Pollution Control Technologies for Small Wood-Fired Boilers. 2001. See p. 21, Table 6. http://www.localenergy.org/pdfs/Document%20Library/AN%20EVALUATION%20OF%20AIR%20Polution%20from%20Biomass%20Boilers.pdf.

chips to garden centers, landscape outlets, and end-users. Consequently, (and one of the assumptions in this study) is that *minor additional emissions if any* are made to the atmosphere in preparing urban tree chips for combustion. Therefore, Table 1 (and Table 2) only consider CO_2 emissions directly related to the *combustion* of urban trees.[18] As an aside, the CO_2 emissions for wood combustion (estimated at 220 lbs. per million BTU) and coal (estimated at 218 lbs.) are nearly equal for practical purposes.

The difference in heat output from burning wood at different MCs is acknowledged in Table 1 with values ranging from 8.5 million BTUs/ton (for wood at 50 % MC) to 17.0 million BTUs/ton (for bone-dry wood).

Macro Level

Table 2 presents various scenarios at a macro-level on burning urban trees as a substitute (displacement) for coal. Table 2 is based on various assumptions from the main body of this report. Specifically, the total volume of carbon storage in urban trees is estimated at 774,146,100 tons with 74 percent, or 572,868,114 tons, in above ground biomass (from Nowak and Crane 2002). The annual removal rate of urban trees is estimated at 1 percent, or 5,728,681 tons of carbon per year (dry weight basis). *Given a 1 percent annual removal rate*, Table 2 shows the coal (fossil fuel) displacement and avoided CO_2e emissions if different percentages of urban trees at 50 percent moisture content (green basis) are combusted in place of coal. For example, if 10% of annual urban tree removals are combusted for electrical power in place of coal, then an estimated 939,500 tons of coal is displaced and 2,113,880 tons of fossil fuel CO_2 emissions are avoided. This is the equivalent of about 1% of annual energy-related CO_2e emissions attributable to coal; the value is also comparable to annually removing over 367,000 passenger cars from U.S. highways.

District Energy St. Paul

District Energy St. Paul served its first customer in 1983 and was St. Paul's response to the energy crises of the mid- and late- 1970s. In 1993, District Energy began offering district cooling to downtown (St. Paul) building owners. In 2003, a combined heat and power plant (CHP) fueled primarily (70%) by urban wood waste began serving the District Energy system. Currently, the CHP plant simultaneously produces 65 megawatts of thermal energy for District Energy and 25 megawatts of electricity for Xcel energy.

After installing the CHP, District Energy reduced its alliance on coal by 70 percent. Today, District Energy burns approximately 280,000 tons of wood annually (clean urban tree trimmings, forest residuals, and other wood waste). The District Energy website notes that it has reduced CO_2 emissions by 280,000 tons per year (http://www.districtenergy.com/services/environmental.html).

The District Energy "case-study" comparing wood burned and reduced CO_2 emissions supports the results of this report where (from Table 1) the burning of one ton of urban tree 'waste' at 50% moisture content (green basis) reduces fossil fuel CO_2e emissions from coal by nearly one ton.

[18] In the Twin Cities of Minnesota, some woody debris from urban trees is directly ground into "energy chips" on-site, bypassing the typical neighborhood chipping done by tree service firms. Also, some small-scale users of "energy chips" in Minnesota do their own chipping (at combustion site) of un-processed woody material (limbs, tops, brush, etc.) delivered to their place of business by tree service firms. Any extra or re-processing of wood to prepare it for combustion is minimal and estimated at less than 5 lbs. of CO_2 per million btu. This estimate is supported by a study that investigated the tub-grinding of corn stover and determined that the grinding (similar to wood chipping) emitted 14.83 kg CO_2e/ton which equates to 3.8 lbs./mm btu for wood at 50% mc, (i.e., 14.83 x 2.2 = 32.626 CO_2e/ton; 32.626/8.5 mm btu = 3.8 lbs./mm btu). See: http://www.biomasschpethanol.umn.edu/papers/ASABE%20096660.pdf.

Table 2. Percent combustion of national urban tree (wood) removals and fossil fuel displacement in tons (coal) and avoided CO_2e emissions.

Percent of Urban Wood Combusted at 50% MC green basis (at 1%/yr. removal rate)	Tons of Coal (Fossil Fuel) Displaced	Tons of Avoided Emissions (CO_2e) from Coal (Fossil Fuel)
1	93,950	211,388 (1)
2	187,900	422,776
3	281,850	634,164
4	375,800	845,552
5	469,750	1,056,940
10	**939,500**	**2,113,880**
15	1,409,250	3,170,820
20	1,879,000	4,227,760
25	2,348,750	5,284,700
50	4,697,500	10,569,400
75	7,046,250	15,854,100
100	9,395,000	21,138,800

Calculations are as follows for the 1% combustion scenario: (774,146,100 tons of carbon sequestered by urban trees) x (.74 above ground) = 572,868,114 above ground tons carbon; (572,868,114 tons above ground carbon) x (1% annual removal rate) = 5,728,681 tons of carbon annually removed from urban forests; (5,728,681) x 2 = 11,457,362 dry tons of woody biomass as trees are 50% carbon; (11,457,362 dry tons) x 2 = 22,914,724 tons green weight [the multiplication is "times 2" since a living tree is ½ water by weight]; (22,914,724) x (1 % combustion) = 229,147 tons of urban trees combusted annually; (229,147) x (0.41) = **93,950 tons** of coal displaced since burning 1 ton of wood at 50% MC (green basis) displaces 0.41 ton of coal (see Table 1 for displacement ratio calculation); (93,950) x (2.25 tons of CO_2/ton of coal) = **211,388 tons** of avoided CO_2 emissions by burning 1% of annual urban tree removals (i.e., burning 1% of the annual 1% removal rate).

(1) Due to rounding, values in both columns in Table 2 will differ slightly depending on the order of the calculations.

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