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Life-cycle analyses, energy analyses, and a range of utilization efficiencies were developed to determine the carbon dioxide (CO_2) and fossil fuel (FF) saved by various solid wood products, wood energy, and unharvested forests. Some products proved very efficient in CO_2 and FF savings, while others did not. Not considering forest regrowth after harvest or burning if not harvested, efficient products save much more CO_2 than the standing forest; but wood used only for energy generally saves slightly less. Avoided emissions (using wood in place of steel and concrete) contributes the most to CO_2 and FF savings compared to the product and wood energy contributions. Burning parts of the harvested logs that are not used for products creates an additional CO_2 and FF savings. Using wood substitutes could save 14 to 31% of global CO_2 emissions and 12 to 19% of global FF consumption by using 34 to 100% of the world's sustainable wood growth. Maximizing forest CO_2 sequestration may not be compatible with biodiversity. More CO_2 can be sequestered synergistically in the products or wood energy and landscape together than in the unharvested landscape. Harvesting sustainably at an optimum stand age will sequester more carbon in the combined products, wood energy, and forest than harvesting sustainably at other ages.

KEYWORDS carbon sequestration, wood products, biodiversity, fossil fuel, global forest growth, sustainable forest management

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INTRODUCTION

Two different forest conservation approaches are being proposed that are each intended to sequester greenhouse gases and to protect forest biodiversity. Greenhouse gases in this article are measured in carbon dioxide (CO_2) equivalents; "CO_2" refers to CO_2, methane, and nitrous oxide as well as carbon in fossil fuel (FF), solid wood products, and forests that could become CO_2. One approach is to minimize harvest and thus store CO_2 in the forest and protect biodiversity through forest preservation. The other approach is to use solid wood products and wood energy that avoid CO_2 emissions from substitute materials and to maintain biodiversity through active management.

The infrastructure of buildings, bridges, and other constructions is expected to triple worldwide with demographic and economic changes by 2050 (Seto, Güneralp, & Hutyra, 2012). Much past construction has been from steel, concrete, and brick; however, wood construction innovations (mgb Architecture + Design, 2012) may avoid much of the CO_2 release and FF consumption associated with these other products (Figure 1). As FF prices rise, wood will increasingly be in demand as a low-energy building material and as energy through direct wood combustion. There is disagreement over whether this increased wood use is complementary or counterproductive to reducing CO_2 emissions and protecting biodiversity.

This article examines CO_2 and FF savings and biodiversity protection through both harvesting and/or not harvesting the forest with four studies:

1. comparing CO_2 and FF savings from harvested products and/or wood energy and the standing forest;
2. determining whether either enough harvestable wood or enough needed construction exists for wood use to have a globally meaningful impact on CO_2 and/or FF savings;
3. determining the relation of forest harvest or preservation to biodiversity and forest CO_2 savings;
4. examining the long-term CO_2 savings from wood harvest and use versus not harvesting the forest.

Both forest sequestration of CO_2 and active use of wood have had considerable analyses (Perez-Garcia, Lippke, Comnick, & Manriquez, 2005b; Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008; Hennigar, MacLean, & Amos-Binks, 2008; Searchinger et al., 2009; Ryan et al., 2010; Lippke et al., 2011; Malmsheimer et al., 2011; Ashton, Tyrrell, Spalding, & Gentry, 2012).

Wood can potentially avoid emitting CO_2 from FF to the atmosphere by several pathways:
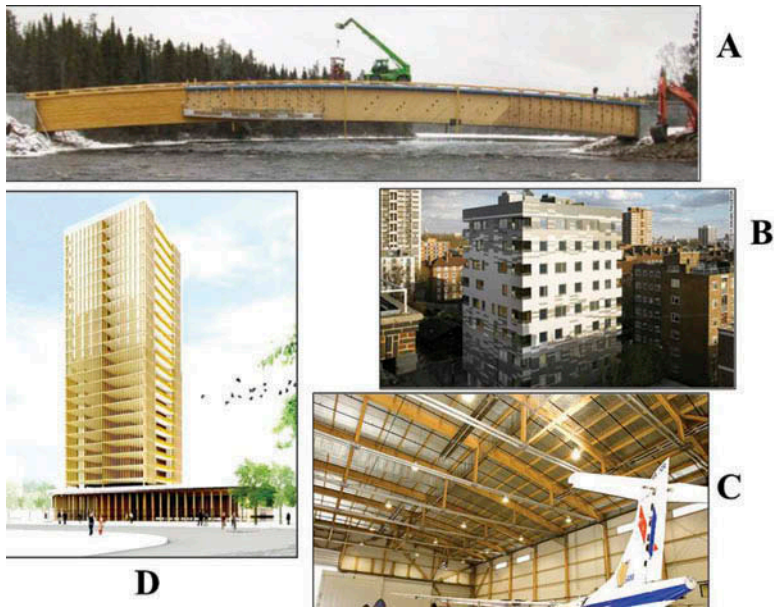
FIGURE 1 Innovative wood construction designs can replace much steel and concrete: (a) high-load wood bridge, Quebec, Canada; (b) Stadthaus—Murray Grove Tower, London, United Kingdom; (c) aircraft hanger in Montreal, Canada; (d) design of 20-story wood building, Vancouver, British Columbia, Canada. ((a) and (c) construction by Nordic Engineered Wood, Chantiers Chibougamau, LLC, Quebec; photo courtesy of Jean-Marc Dubois. (b) designed by Waugh Thistleton Architects, London; photo courtesy of Will Pryce, London. (d) of designed building, MGA, Michael Green Architecture, Brooklyn, New York, and Vancouver, British Columbia.)

- forest pathway (FP): sequestering CO_2 in the standing forest;
- storage pathway (SP): storing wood in the products so it does not rot or burn and produce CO_2;
- energy pathway (EP): displacing CO_2 produced by burning FF with CO_2 produced by burning energy;
- avoidance pathway (AP): substituting wood for steel, concrete, and other products that use more energy in their manufacture, thus consuming less FF and emitting less CO_2;
- landfill pathway (LP): storing waste wood in landfills where it either does not decompose or decomposes and emits methane and other greenhouse gases.

Wood can also save FF by the avoidance and energy pathways.

Each pathway has uncertainties that could sway analyses for or against any forest preservation or wood use scenario. For example, recovered wood from demolished buildings could be put into landfills where methane could be emitted or it could be reused as solid products or wood fuel that save

CO_2. This study assumes "reasonable conditions" occur; that is, the forests, wood use, and waste disposal are treated in conscientious ways that avoid extremely negative consequences. In addition, this study examines a range of wood use efficiencies to determine the potential range of CO_2 and FF savings.

Harmon, Ferrell, and Franklin (1990), Krankina and Harmon (1994), Harmon and Marks (2002), Kristin and Raymer (2006), Seidl, Rammer, Jäger, Currie, and Lexer (2007), Seidl, Rammer, Lasch, Badeck, and Lexer (2008), and Nunery and Keeton (2010) found more CO_2 was saved by limiting wood harvest and storing carbon in the forest; however, many of these studies did not include the avoidance pathway. Other analyses have found more CO_2 was saved by utilizing solid wood products (Oliver, Kershaw, & Hinckley, 1991; Kershaw, Oliver, & Hinckley, 1993; Kauppi et al., 2001; Perez-Garcia et al., 2005b; Petersen & Solberg, 2002; Hennigar et al., 2008).

Wood has been reported to save CO_2 when used as a fuel (Manley & Richardson, 1995; Hoogwijk et al., 2003; Seidl et al., 2007; Seidl et al., 2008). However, others claim that harvesting wood for fuel is not an immediate CO_2 savings, and whether it contributes to fossil fuel savings depends on the waiting period before carbon is re-sequestered by the growing forest (O'Laughlin, 2010).

Equally important, will either forest preservation or wood use have meaningful enough global CO_2 and FF savings to justify promoting any policies? There are 3.9 billion ha of forest (3.9×10^9) in the world (United Nations-Food and Agriculture Organization [UN-FAO], 2007). Luyssaert et al. (2007) estimated that 8.4 billion (milliard) tonnes of aboveground woody biomass are produced each year as net primary production, or 21 billion m^3/yr. Haberl et al. (2007) estimated that approximately 1 billion tonnes of forest carbon are harvested annually, equivalent to 5.2 billion m^3/yr. Schulze, Korner, Law, Haberl, and Luyssaert (2012) estimated that more than doubling the estimated forest harvest would be needed to reduce FF energy consumption by 20%, presuming the wood is used for energy production (energy pathway). By contrast, FAOSTAT (2012) reported that the world is harvesting 3.4 billion m^3/yr (3.4×10^9) of wood, of which 32% was used for construction, 15% for pulp/paper, and 53% for fuelwood. Most of this fuelwood is burned very inefficiently at present.

Using the FAOSTAT (2012) estimate, the world is harvesting an average of 0.9 m^3/ha. Much of the world's forests grow faster than this average harvest. Carle and Holmgren (2008) have found that planted forests occupy only 7% of the world's forest area, but grow 41% of the amount of wood globally harvested by the estimate of FAOSTAT (2012). It is highly likely that the world could harvest much more wood and still harvest sustainably (Oliver, 2001)—that is, harvest no more than is growing.

Schulze et al. (2012) are concerned that harvesting more of the world's forest growth could adversely affect ecosystems. A common assumption is
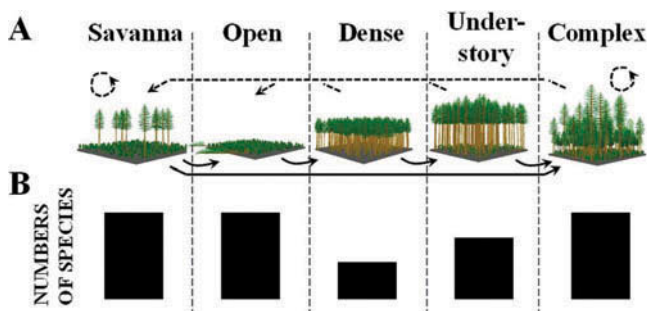
FIGURE 2 Forest landscapes naturally contain a dynamic diversity of stand structures: (a) as individual stands grow (solid lines) and are disturbed (dashed lines); (b) different species depend on each structure, with more species generally depending on the savanna, open, and complex structures than the dense and understory.

that greater CO_2 savings and greater biodiversity will result from avoiding forest harvest (Grainger et al., 2009; Paoli et al., 2010). Biodiversity is being promoted by establishing reserved forests, where forest harvest is prohibited. On the other hand, not all species live in old, closed forests that develop if a forest grows a long time without natural or human disturbances. Rather, forests have contained stands in a variety of structures for millennia (Figure 2), and different species have evolved that depend on each structure (Oliver, 1992; Oliver & Larson, 1996). The savanna, open, and complex structures support the most species; however, each structure supports different species, so all structures are necessary to avoid species extinctions.

At present, the world's current 3.9 billion ha of forests have been fragmented and reduced by much of the 1.6 billion ha of cropland (UN-FAO, 2010) and by other human activities. Remaining forests in many parts of the world do not contain a balance of structures (Oliver & Deal, 2007; Han, Oliver, Ge, Guo, & Kou, 2012). Consequently, species are endangered that require various structures that are regionally lacking (Oliver, 1992; Oliver & O'Hara, 2004). The present fragmentation, reduction in forest area, and imbalance of structures may mean that it is prudent for active management to provide the diversity of structures (Oliver, 1992) rather than anticipate that natural processes will return the diversity. In the process of this active management, some trees can be harvested and utilized. Seymour and Hunter (1999) have proposed management in which part of each forest is set aside as reserves and others are actively managed to provide a diversity of structures and other values. Currently, 12.5% of the world's forest area is in such reserved areas (UN-FAO, 2000).

Some structures probably sequester less CO_2 than others. Maintaining all structures within a forest to ensure biodiversity may necessitate providing structures that sequester relatively little carbon, and hence may not be completely compatible with sequestering the most CO_2 in a forest.

Forests exist under a variety of climatic, edaphic, physiographic, and biotic factors (Toumey, 1928). Some forests accumulate biomass and thus sequester CO_2 (Nunery & Keeton, 2010); others are relatively stable (Harmon et al., 1990); and others release CO_2 through disturbances (Oneil & Lippke, 2010). Furthermore, a diversity of stand structures (Figure 2) can reduce a forest's susceptibility to catastrophic fires that drastically reduce the amount of closed structures (dense, understory, and complex) and release much CO_2. Both regions and forests of high fire susceptibility can be identified, and prudent silvicultural interventions can be taken to minimize the catastrophic fires.

Even in forests with a low danger of catastrophic fires, differences in the calculated forest carbon savings or loss from harvest is because different analyses address the impacts immediately after harvest (Marland & Schlamadinger, 1997; O'Laughlin, 2010) or after forest regrowth (Perez-Garcia et al., 2005b; Fargione et al., 2008; Hennigar et al., 2008; Searchinger et al., 2009). Some studies examine future opportunities to sequester more CO_2 in forests (forest pathway) and analyze the "opportunities lost" if the forest is harvested (Harmon et al., 1990; Nunery & Keeton, 2010).

A "debt-then-dividend" consideration has been suggested (Searchinger et al., 2009) where a harvested stand may first create a net decline in CO_2 savings, but create an even greater savings as it regrows. Others point out that forest carbon, as well as biodiversity and other values, needs to be examined across a landscape of many stands (Oliver, 1992; Perez-Garcia et al., 2005b; Ryan et al., 2010; Malmsheimer et al., 2011). Individual stands fluctuate widely in CO_2 sequestered with harvest and regrowth, but these fluctuations are offset across the landscape (O'Laughlin, 2010; Ryan et al., 2010) with other stands being harvested and regrowing at different times.

Analyses seeking to store CO_2 in products and/or wood energy sometimes assume that there will be no net loss of CO_2 from the forest if it is harvested sustainably (Malmsheimer et al., 2011). On the other hand, the amount of CO_2 saved sustainably in the combined products, wood energy, and forest may vary with harvest age as the mean annual increment changes.

Policymakers are receiving mixed signals of whether to promote CO_2 savings in the forest, wood products, or wood energy. Forest certification (Cashore, Auld, & Newsom, 2004) and various carbon credits (Cairns & Lasserre, 2006) and REDD+ (Corbera, Schroeder, & Springate-Baginski, 2011) encourage forest management to provide carbon sequestration and other values such as biodiversity in the forest. Other policies are being considered to harvest forests for CO_2 reductions and FF savings (Cubbage, Harou, & Sills, 2007; Richter et al., 2009). The above issues need to be clarified before policies can be crafted that promote desired goals such as biodiversity protection, CO_2 sequestration, and FF savings (Ruddell et al., 2007).

METHODS

CO_2 and FF Savings With Wood Products, Wood Energy, and Unharvested Forests

The National Research Council (1976) compared FF savings by using wood alternatives to steel, concrete, brick, and aluminum building materials in the 1970s. Results found wood to be very favorable to all other materials in saving both CO_2 and FF (Oliver et al., 1991; Kershaw et al., 1993; Perez-Garcia, Oliver, & Lippke, 1997).

The analyses were redone comparing wood with steel and concrete by the Consortium for Research on Renewable Industrial Materials (CORRIM; Lippke, Wilson, Perez-Garcia, Bowyer, & Meil, 2004), a consortium of 17 research institutions. We further analyzed a range of paired wood/substitute (steel or concrete) wall and floor assemblies (Table 1) that had been analyzed for their CO_2 and FF impacts throughout the life cycle in different parts of the United States (Lippke et al., 2004; CORRIM, 2005a) using the Athena Environmental Impact Estimator (ATHENA Institute, 2004) and life-cycle data from the National Renewable Energy Laboratory (NREL, 2009).

For each wood and substitute product, we calculated total wood and fuelwood used by weight, CO_2 emitted, and FF consumed using a wood heating value of 13.9 MJ/kg (CORRIM, 2005b; Lippke, Wilson, Johnson, &

TABLE 1 Wood and Nonwood Building Components Analyzed for This Study (Lippke & Edmonds, 2006, 2009)

Abbreviation	Symbol in figures	Explanation
BioDried Stud	WS	Wood wall column (stud), dried using wood energy
BioDryStud/BioDryPly/ BioDryPly	WS & PC	WS and plywood on interior & exterior (sheathing) dried using wood energy
Steel Stud	SS	Steel wall column (stud) to functionally replace WS
Concrete Block/Stucco	CB & SC	Concrete block wall with stucco exterior to functionally replace WS & PLY & PLY
Dimension Joist	WB	Wood beams (joists) to support floor
EWP I-Joist	WI	Engineered wood product (EWP) to functionally replace WB
EWP/Ply	WI & PLY	WI covered with plywood dried using wood energy
Steel Joist	SB	Steel joist to functionally replace WB or WI
Concrete Slab	CS	CS laid on ground to functionally replace WI & PLY on ground floor
Steel Joist/Concrete Slab	SB & CS	We "created" a raised concrete floor by underpinning the ground concrete slab with steel joists. (Probably more energy/ material is needed than calculated here.)

Puettmann, 2010a). Values are reported on the basis of CO_2-equivalents using Global Warming Potential (GWP) for a 100-yr time horizon (Forster et al., 2007). Wood products were assumed to be 50% carbon, and CO_2 was calculated at 3.667 kg CO_2/kg carbon. This article assumed all nonwood energy in the life-cycle analyses would come from FF with a value of 0.08 kg CO_2/MJ of energy based on CORRIM data; this value is consistent with the CO_2 emissions from burning FF analyzed for wood energy (Table 2). The concrete slab analyzed by CORRIM was placed directly on the ground; however, this study virtually suspended the concrete slab onto steel joists in one analysis and compared wood to this suspended concrete and steel floor.

Net CO_2 changes were separated into storage, energy, and avoidance pathways. The FF CO_2 emissions generated during wood use were subtracted from the avoided emission generated by nonwood substitutes. FF changes were segregated into similar energy and avoidance pathways.

Building life spans and CO_2 and FF outputs for living (e.g., heating and cooling), repair, and demolition were very similar for buildings made from all products (Perez-Garcia et al., 2005a; Winistorfer, Chen, Lippke, & Stevens, 2005; Werner, Taverna, Hofer, & Richter, 2006; Lippke, Wilson, Meil, & Taylor, 2010b), so "cradle to gate" life cycles of functionally equivalent

TABLE 2 CO_2 and FF Data and Analysis for Wood Burned for Energy

	Energy content (MJ/kg wood)	
Wood fuel	Technical low[d]	Technical high[e]
Wood energy content[a]	13.9	20.9
Harvesting/processing[b]	−3.78	−6.24
Net energy yield of wood[c]	10.12	14.66

	CO_2 emissions intensity (kg CO_2-eq./MJ)		
Fossil fuel type[f]	Lower[i]	Average[j]	Upper[k]
Natural gas	0.05	0.06	0.06
Residual fuel oil[g]	0.08	0.08	0.08
Lignite[h]	0.09	0.10	0.12

	Net CO_2 emission savings from substitution (kg CO_2-eq./kg wood)		
Wood fuel substituting for:	Technical low/lower[l]	Technical average[m]	Technical high/upper[n]
Natural gas	0.55	0.70	0.86
Residual fuel oil	0.76	0.97	1.17
Lignite	0.92	1.31	1.71

Note. Superscripts a & b, see text; c = a − b; i & k from Burnham et al. (2011), see text; j = (i + k)/2; l = c:d × i; n = c:e × k; m = (l + n)/2.

wood, steel, and concrete products are compared here. Comprehensive life-cycle analyses have not been done for hardwoods and for cross-laminated timber (CLT) used in modern high-rises (mgb Architecture + Design, 2012). CLT was assumed to have CO_2 and FF efficiencies similar to solid wood beams. Analyses of some products suggest hardwood results are similar to conifers (Bergman & Bowe, 2012). This study assumed hardwoods could be used with the same range of efficiencies as the conifers studied.

We also analyzed CO_2 and FF savings for wood burned directly for energy instead of used in construction (Table 2). Wood can be burned at a theoretical energy efficiency maximum of 28.2 MJ/kg of wood, and recent industrial and pellet stoves generate values up to 20.9 MJ/kg of wood (Lehtikangas, 2001). The CO_2 saved by wood energy was compared with natural gas, residual fuel oil, and lignite (Intergovernmental Panel on Climate Change [IPCC], 2006; Burnham et al., 2011). These CO_2 emission intensities were the CO_2-equivalent units using global warming potential values (Burnham et al., 2011) for a 100-yr time horizon. Lignite was used to assess a wide range of CO_2 values, even though bituminous and anthracite coals are more commonly used.

Forest harvesting generally generates some logs that are "unmerchantable"—the wrong size, shape, or species to make into solid products (Figure 3). The "merchantable" proportion of harvested logs varies with harvesting and processing technologies. In addition, only about 50% of the merchantable log is made into solid products when milled (Perez-Garcia et al., 2005b), with the remainder becoming "scrap-wood"—sawdust, slabs, and bark. Some of this scrap-wood can be burned for energy to make the product (energy pathway). This article assumes that all unmerchantable logs are removed from the woods. The solid wood product portion of merchantable logs was calculated for CO_2 and FF savings for the products in Table 1. The scrap-wood used as product fuel was subtracted from the nonproduct half of the merchantable log weight, and the remaining scrap-wood and unmerchantable logs were assumed to be burned directly for energy as a FF substitute that also avoids CO_2 emissions (Table 2). Both the high and low CO_2 emission intensity and FF energy values were calculated for the scrap-wood and unmerchantable logs burned directly for energy.

The instantaneous effect of harvest is to remove stem wood from the forest. Over time, dead foliage and branches rot, new foliage and trees grow, and the soil and other forest carbon pools adjust to changes (e.g., Laiho, Sanchez, Tiarks, Dougherty, & Trettin, 2003). Other carbon pools are generally calculated as proportional to stem wood (Perez-Garcia et al., 2005b); however, the adjustments of these pools is not rapid. For purposes of this study, total stem carbon is used as a better indicator of total forest carbon than total carbon calculated through proportions to stem wood. (For example, immediately after harvest, the dead or regrowing limb, root, and soil
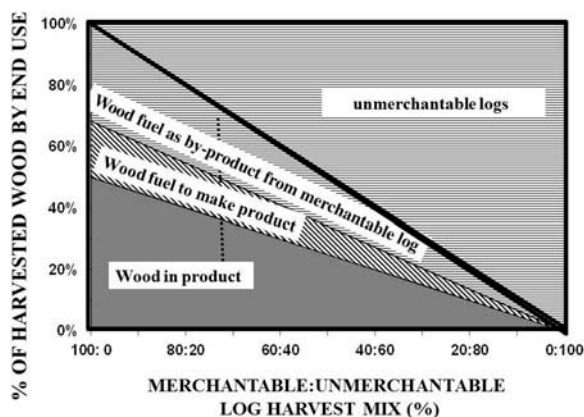
FIGURE 3 Distribution of harvested wood from logging and milling operations with stems used in different proportions of merchantable-to-unmerchantable logs by weight. Some wood from merchantable logs is made into products, and the rest becomes "scrap-wood" that is used for fuel. Some scrap-wood fuel is used to manufacture the product and other is simply a by-product. All unmerchantable logs become by-product fuels. Dashed lines show 70%:30% values used in subsequent analyses.

carbon do not immediately adjust to the very low amount of stem carbon remaining.)

Global Availability of Wood and Potential Global Consumption

To determine if an increase in wood use could markedly change the world's CO_2 emissions and/or FF consumption, it was necessary to determine both the impact of nonwood construction on global CO_2 and FF changes and how much wood could potentially be grown worldwide.

The world consumes approximately 0. 41 quadrillion MJ/yr (4.1×10^{14}) of fossil fuel (2010 basis; Energy Information Administration [EIA], 2011). The energy consumed globally from producing steel, concrete, brick, and aluminum was calculated by multiplying the global annual production by the embedded energy of each product (Table 3). These materials consumed 17% of the world's total FF energy, not including transportation and assembly in buildings. Only a portion of these materials are used in construction; so we conservatively identified 10% as the proportion of FF energy used for nonwood building materials that could be saved by using wood materials instead (avoidance pathway).

The potential global forest growth rate under nonintensive management was calculated from the literature to determine how much wood could be harvested sustainably in the world. The world's forest had been stratified into ecoregions and areas by the UN-FAO (2007). We assessed forest growth rate for each ecoregion from the literature on forest growth of states, provinces,

TABLE 3 Estimates of Global FF Energy Consumed by Various Nonwood Construction Products; Embedded Energy Shows Ranges

Construction material	2010 global production (kg)	Embedded energy estimate (MJ/kg)[c]	Total FF energy consumed (MJ)[d]	Percent of global FF consumed[e]
Steel	$1.4E + 12$[a]	25 (8.8[e] to 48.4[f])	$3.6E + 13$	9%
Concrete	$2.2E + 13$[a]	1 (0.5 to 2.1)	$2.2E + 13$	5%
Brick	$2.0E + 12$[b]	5 (3 to 8)	$1.0E + 13$	2%
Aluminum	$4.1E + 10$[a]	100 (24[e] to 218[f])	$4.1E + 12$	1%
		Total	$7.2E + 13$	17%

Note. Superscript a from (U.S. Geological Survey, 2011); b from (EIA, 2011); c from (Hammond & Jones, 2008); d from (Hammond & Jones, 2008; EIA, 2011); e = recycled; f = virgin.

or countries where they could be identified by ecoregion (Table 4; UN-ECE/FAO, 2000; Clark et al., 2001; Evans & Turnbull, 2004; Smith, Miles, Perry, & Pugh, 2009; Fredericksen, 2011; Fuwape, 2011). Intensive plantation growth data were not used. Clark et al. (2001) listed aboveground Net Primary Production (NPP) for some forests; stem growth was estimated as 70% of this NPP, based on (Gholz, 1982). Conservative estimates were made where no data was available for an ecoregion, primarily in regions of very low productivity. The resulting estimate of 6.5 billion (milliard) tonnes of stemwood/year (Table 4) is similar to the aboveground NPP estimate of 8.4 billion tonnes of aboveground woody biomass by Luyssaert et al. (2007).

The range of CO_2 and FF that could be saved was determined by substituting various wood building materials for other materials (Table 1) until either no more structures needed building or global wood growth was completely used. Merchantable logs were assumed to be 70% of the total harvested stem volume.

The analyses were streamlined by assuming "instantaneous" use of additional wood solely for wood construction or wood energy under current circumstances; thus, the added uncertainties of future changes in pulpwood use, total construction, accelerated forest growth, or lag times in increasing wood use were avoided.

Stand Structures, Biodiversity, and CO_2 Sequestration

To determine the impact of different stand structures on forest CO_2 sequestration, two forest landscapes were examined:

- 32 stands constituting a part of Pack Forest (University of Washington), a productive, conifer forest (average site index of 31 m at 50 yr) of 284 ha in western Washington, USA; and

TABLE 4 Potential Forest Wood Growth, Based on Literature Stratified by UN Ecoregions; Potential Growth Refers to Growth From Normally Managed Forests (Excluding Intensive Plantations)

United Nations Food and Agriculture global ecoregions[a]	Estimated average potential timber growth[b] (m³/ha/yr)	Forest area[c] (10⁶ ha)	Potential global forest growth Volume[d] (10⁶ m³)	Mass[e] (10⁹ kg)	Sources
Tropical rainforest	8	1,004	7,929	3,048	Clark et al., 2001
Tropical moist deciduous forest	7	355	2,485	955	Clark et al., 2001; Evans & Turnbull, 2004
Temperate oceanic	6	46	282	109	Smith et al., 2009; UN-ECE/FAO, 2000
Tropical dry	6	430	2,367	910	Clark et al., 2001; Evans & Turnbull, 2004; Fredericksen, 2011
Subtropical mountain	5	112	562	216	Smith et al., 2009
Subtropical humid	4	156	610	234	Smith et al., 2009
Tropical shrub	3	71	219	84	Clark et al., 2001; Fuwape, 2011
Temperate continental	3	248	719	276	Smith et al., 2009; UN-ECE/FAO, 2000
Subtropical dry	3	55	148	57	UN-ECE/FAO, 2000
Temperate mountain	3	195	487	187	Smith et al., 2009; UN-ECE/FAO, 2000
Boreal coniferous	2	580	870	334	UN-ECE/FAO, 2000
Boreal mountain	1	329	165	63	No data (estimated)
Tropical mountain	1	111	56	21	No data (estimated)
Boreal tundra	1	96	48	18	No data (estimated)
Subtropical steppe	1	48	24	9	No data (estimated)
Temperate steppe	1	31	15	6	No data (estimated)
Subtropical desert	1	12	6	2	No data (estimated)
Temperate desert	1	8	4	2	No data (estimated)
Tropical desert	1	2	1	0	No data (estimated)
Polar	0	16	0	0	No data (estimated)
Total		3,906	16,996	6,534	

Note. Superscript a = UNFAO ecoregions (UN-FAO, 2007); b = average forest growth from multiple sources; c = average area of each ecoregion (UN-FAO, 2007); d = b × c; e = d × 0.3844 kg/m³.

- 64 stands constituting Bent Creek Experimental Forest (U.S. Forest Service), a moderately productive, predominantly mixed species hardwood forest (average site index of 24 m at 50 yr) of 2,474 ha in western North Carolina, USA.

Inventories of both forests were downloaded through the Landscape Management System platform (McCarter, 2013), and the total tree stem standing volume and stand structure of each stand at time of inventory was determined using the Landscape Management System (Oliver, McCarter, Ceder, Nelson, & Comnick, 2009). Standing volume was converted to kg CO_2 sequestered/ha using wood densities of 418 kg/m^3 for conifers and 500 kg/m^3 for mixed hardwoods.

Forest CO_2 Sequestration, Forest Growth, and Wood Use Interactions

Catastrophic forest fires immediately release CO_2 to the atmosphere and release more if the charred, dead stems burn again in subsequent fires. The energy released does not offset FF CO_2, so there is no CO_2 or FF savings. Consequently, there would be emissions of CO_2 and added consumption of FF by not avoiding the catastrophic fires or by not harvesting these forests before they burned.

Many forests do not burn; however, even unburned forests may sequester less CO_2 if not harvested than if harvested for products and/or wood energy and allowed to regrow. To examine the CO_2 relations of harvesting and not harvesting forests that do not burn, we developed a "best case" scenario using forests that are not burned in catastrophic disturbances of the relation between CO_2 sequestered in the combined products/wood energy/and forests, time since harvest, and sustainable rotation age. Data from a 150-yr chronosequence (McArdle, Meyer, & Bruce, 1961) of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) forests were used to compare CO_2 savings by harvesting with allowing the forest to grow. This data collected before 1930 was used to ensure that younger forests in the sample would not have been subjected to intensive management, and so had grown similarly to older sampled forests. The data contained forest volume averages for 10-yr intervals, stratified by productivity. A high productivity stratum was used (Site Index 49 m at 100 yr). The data were cubic volumes/acre of stems greater than 15.2 cm diameter at 1.4 m height; these were converted to CO_2/ha of stemwood using wood densities of 418 kg/m^3. Only stemwood carbon was considered, for reasons described earlier.

For conceptual simplicity, this study assumed harvest and regrowth across the landscape in a fully regulated forest that is sustainably managed by even-age harvesting an equal area each year. More complex, sustainable

harvesting analyses that maintain all structures are possible (Oliver et al., 2009), but do not change to conceptual results of the present inquiry.

RESULTS

CO_2 and FF Savings With Wood Products, Wood Energy, and Unharvested Forests

Comparisons of wood with substitute products and FF energy (Figure 4a–b) show a very wide range of CO_2 and FF savings can be gained, depending on the product. These results are consistent with an average total savings of 3.9 kg CO_2/kg of wood estimated from a meta-analysis by Sathre and O'Connor (2010). The National Research Council (1976) data had shown that kiln-fired bricks and aluminium are even more CO_2 and FF intensive than concrete and steel (Oliver et al., 1991; Kershaw et al., 1993).

The greatest gains of both CO_2 and FF savings in forest products are through avoiding FF needed to manufacture, transport, and construct with steel or concrete (avoidance pathway; Figure 4a–b). For CO_2 savings, slightly less carbon is generally stored in the wood product (storage pathway) than was used because some wood is removed and burned for energy to manufacture the product. Compared to avoidance and storage pathways, relatively little CO_2 and FF are saved by the wood energy used to manufacture wood products. Unless extremely efficient, wood burned solely for energy (energy pathway) without being the residual of wood product manufacture saves less CO_2 than was in the unburned wood. Wood energy can save FF, although less than using wood for most solid products (Figure 4b).
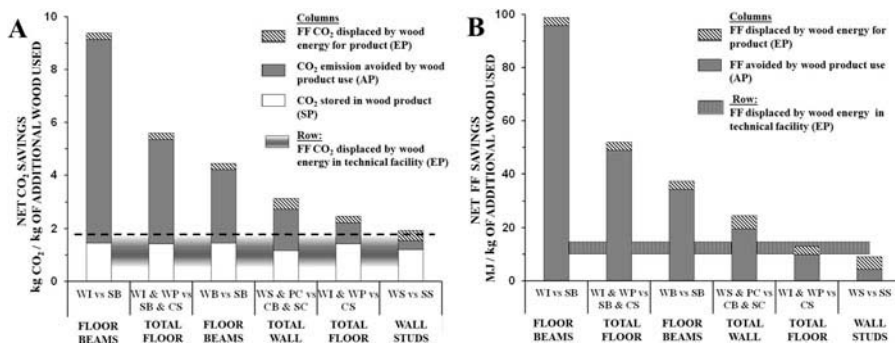

FIGURE 4 CO_2 and FF savings efficiencies of wood products compared to alternative steel and concrete building components: (a) CO_2 emissions savings and (b) FF savings when substituted for various steel and concrete building components or burned for energy. For (a), darker shading of bar = more conservative values; dashed line = immediate CO_2-equivalent stored in unprocessed wood. (See Table 1 for horizontal axis terminology; AP, SP, & EP = FF and CO_2 storage pathways.)
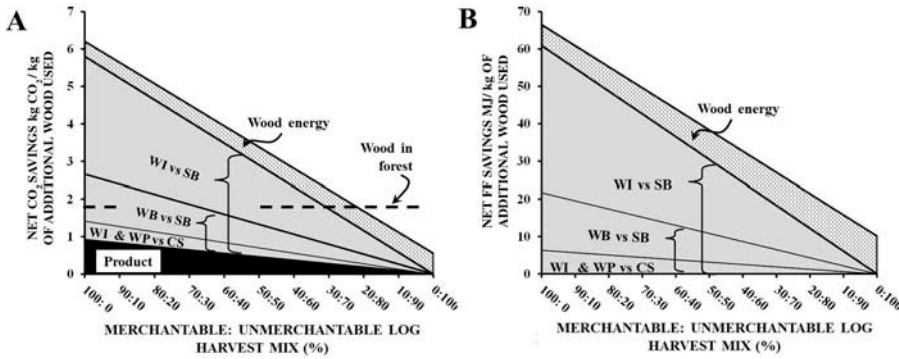
FIGURE 5 CO_2 (a) and FF (b) saved with different product and processing efficiencies (Figure 3) and different merchantability standards (Figure 2). Gray shows avoidance pathways for three comparisons (Table 1). Hatching shows average energy pathway with inefficient burning of wood. Black in (a) shows product pathway. Horizontal dashed line in (a) shows forest CO_2 lost instantly by harvesting stems.

When harvesting and milling are considered (Figure 5a–b), the overall efficiency of wood use is less than Figure 4a–b because not all wood can be used for solid products. A wide range of savings can be obtained depending on the specific wood building material, the nonwood product being replaced, the amount of harvest that can be used for products (merchantable logs), and the efficiency of burning the scrap-wood and unmerchantable logs for energy.

With efficient product use and harvesting, more CO_2 is saved in the avoided emissions, products, and wood energy than is lost instantaneously from the harvested forest. Energy from burning the nonproduct scrap-wood and unmerchantable wood contributes an additional CO_2 and FF savings during the manufacture of wood products (Figure 5a–b), but not as effectively as if this wood had been used to make most products.

Global Availability of Wood and Potential Global Consumption

The global harvest of 3.4 billion m^3/yr (3.4×10^9; UN-FAO, 2012) and estimated growth of 17 million m^3/yr (Table 4) indicate that the world is currently harvesting about 20% of the forest's potential growth if managed with moderate intensity. The additional wood that needs to be harvested to replace steel and concrete so that the world's FF energy consumption is reduced 10% annually through construction savings (avoidance pathway) varies dramatically with efficiency of wood product (Figure 6a). In the most efficient case (wood I-joists substituting for steel joists), an additional 14% of the world's wood growth would be needed beyond the 20% already harvested. Building with less efficient wood products requires more wood to
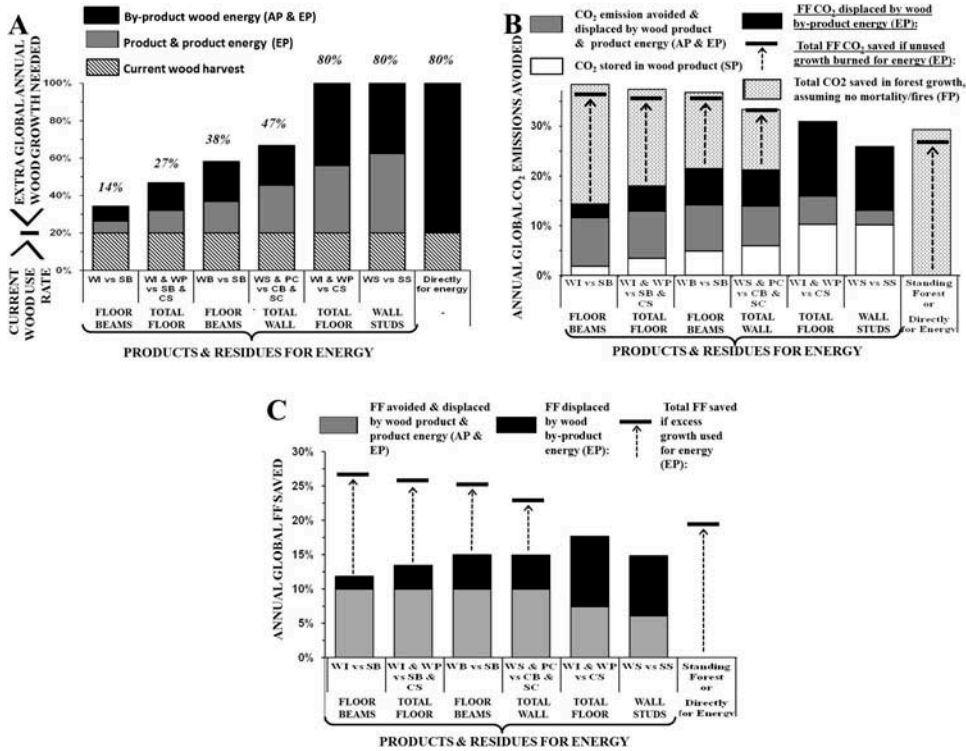
FIGURE 6 Global impacts of wood use for different products to avoid FF lost in construction (estimated at 10% of global annual FF consumption): (a) proportion of global annual wood growth used, numbers above columns show extra wood harvested; (b) proportion of annual global CO_2 emissions avoided; (c) proportion of annual global FF consumption saved. Arrows to bars show CO_2 and FF saved if extra wood growth is utilized for wood energy. (A 70:30 merchantable/unmerchantable harvest ratio is assumed.)

replace the target 10% energy saving. An additional 38% of the growth would need to be harvested if wood beams (comparable to CLT used in high rises; mgb Architecture + Design, 2012) were used. And, inefficient wood products run out of wood growth before they reach that target.

The global FF savings by wood construction would actually be between 12 and 15% instead of just the 10% conserved by the construction itself (avoidance pathway; Figure 6c) because additional wood energy from the accompanying scrap-wood and unmerchantable logs would replace FF energy (energy pathway). The less efficient products save more total FF because they use more wood and so generate more wood energy from scrap-wood and unmerchantable logs. (Notice that the "WI & WP vs CS" saves the most total FF energy through both the avoidance and energy pathways even though it cannot replace all of the targeted 10% construction FF of the avoidance pathway.)

Between 14 and 31% of the world's CO_2 emissions from FF (Figure 6b) could be avoided in the combination of CO_2 stored in the wood products (storage pathway), CO_2 avoided (avoidance pathway), and FF displaced (energy pathway). Building with less efficient wood products also sequesters even more FF CO_2, largely because less efficient products both use more product wood (storage pathway) and burn more scrap-wood and unmerchantable logs that displace more FF energy (energy pathway).

In efficient cases, less wood would be harvested than is growing, so the forests and harvest rates would be more than sustainable; in fact, the unharvested wood could accumulate in some forests and save even more CO_2 (forest pathway). If none of the unharvested wood growth burned or rotted, CO_2 savings would be greatest by using wood for efficient building products, but not harvesting the excess that would only be used directly for energy. This strategy is probably unrealistic because it is impossible to keep all forest wood from rotting, burning, or being harvested. Alternatively, if all wood growth were harvested and used directly for energy, approximately 19% of the world's FF and 27% of the world's CO_2 could be saved. And, FF savings as high as 27% and CO_2 savings of up to 37% could be realized if the 15 to 38% of wood growth were used for efficient products and remaining growth were harvested and used directly for wood energy. The current results are similar to Schulze et al. (2012), who analyzed wood used directly for energy and suggested that 20% of the FF consumption could be reduced by using 60% of the wood growth.

Stand Structures and CO_2 Sequestration

Table 5 shows the amount and variation in stem CO_2 sequestered in different stand structures in the conifer and mixed hardwood forests. Maximum forest CO_2 savings would be accomplished by keeping all forests in the understory and complex structures; however, this would preclude species that depend on other structures—especially savannas and openings.

In fragmented forests with an imbalance of structures, experience suggests that we have not been able to rely on natural processes of disturbances and growth to restore all structures in a timely manner in order to maintain biodiversity (e.g., Oliver & O'Hara, 2004; Oliver & Deal, 2007; Han et al., 2012). Rather, even if stands in the complex structure are preserved to accumulate biomass, some other stands may need to be harvested to create or maintain sufficient open and savanna structures—and to allow these stands to regrow to the dense and understory structures. In the process, the wood removed could be used for construction and energy to save FF CO_2 and FF energy.

Other concerns of nutrient depletion by forest harvest can be partly mitigated by avoiding removal of tree foliage, buds, small twigs, roots, and the

TABLE 5 CO_2 Sequestered in Different Stand Structures in a Productive Conifer Forest and a Moderately Productive Hardwood Forest; the Number of Stands in the Stages Reflects the Common Pattern of Small Amounts of Savanna, Open, and Complex Structures Because of Past Human Activities (Oliver & Deal, 2007)

	Savanna	Open	Dense	Undestory	Complex
Productive conifer forest					
CO_2 (kg/ha)	5.10E + 05	2.80E + 03	2.60E + 05	9.10E + 05	1.20E + 06
Standard deviation	3.90E + 05	1.40E + 04	7.30E + 04	2.30E + 05	1.50E + 05
# stands in sample	4	7	12	9	3
Moderately productive, mixed hardwood forest					
CO_2 (kg/ha)	4.00E + 05	0	3.00E + 05	5.00E + 05	4.40E + 05
Standard deviation	1.50E + 05	0	6.10E + 04	2.30E + 05	4.50E + 04
# stands in sample	2	7	21	31	3

soil where most nutrients are found; and by harvesting on longer rotations so nutrients rebuild between harvests.

Forest CO_2 Sequestration, Forest Growth, and Wood Use Interactions

For those forests that do not burn in catastrophic fires, the carbon change in the forest can be included in the CO_2 analyses (Figure 7a–b). The immediate effects of harvest/product/wood energy use can be positive or negative, depending on whether more CO_2 is stored by product and wood energy use than was in the forest.

A stand that does not burn accumulates carbon rapidly when young, but less as it ages (Figure 8a). Harvesting for wood products/wood energy that immediately save CO_2 (Figure 5a) sequesters even more CO_2 as the forest regrows (Figure 8b). Even harvesting for inefficient products or wood energy that create an initial net CO_2 loss (Figure 7b) can sequester more CO_2 in the combination of products, wood energy, and forest than in the unharvested forest provided the stand regrows long enough (Figure 8c) through the "debt-then-dividend" pattern (Fargione et al., 2008; Searchinger et al., 2009). If the forest would burn unless harvested or partially harvested, even greater CO_2 savings would be achieved by harvesting. And, across a landscape, harvesting so that a diversity of stand structures is created and maintained would both reduce fire danger (Camp, Oliver, Hessburg, & Everett, 1997) and increase biodiversity (Oliver & O'Hara, 2004).

Figure 9a shows the mean annual increment (MAI) and Figure 9b shows the cumulative increment of CO_2 stored by harvesting for different products (with residual wood used for wood energy) in a regulated Douglas-fir forest. It also shows the MAI and cumulative carbon sequestered in stems on the average hectare of the forest (assuming total forest carbon is proportional to stem carbon, described earlier). Harvesting sustainably across a landscape creates no net loss in forest carbon because the same amount of wood is
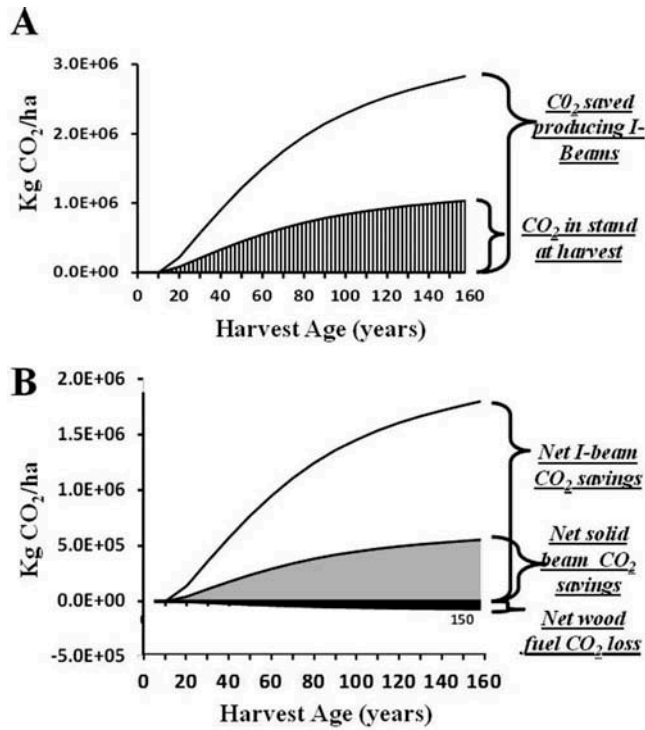
FIGURE 7 Comparison and net effects of CO_2 stored in product and forest when forest growth is not considered in the analysis (immediate effects): (a) immediate effects of CO_2 savings by efficient wood use (I-beam; Figure 5a) and by not harvesting forest; (b) net, immediate storage/loss of total CO_2 by products of different efficiencies (Figure 5b, and 4a for wood fuel) when subtracting carbon in harvested forest.

harvested each year as growth. However, the amount of wood that can be harvested sustainably—and the amount of wood products to save CO_2 (and FF)—varies considerably depending on the target harvest age in a regulated forest (Figure 9), even though all harvest ages could be sustainable.

   Forest carbon stored within the sustained forest landscape (forest pathway) is the average of all stands and would also vary with harvest age (Figure 9). Such harvesting would provide net carbon sequestration as long as harvested wood sequestration were above this average carbon sequestration of the forest. Consequently, harvesting even for inefficient CO_2 storage (e.g., wood fuel) could be a net CO_2 savings in a sustainable forest landscape (Figure 8c & Figure 9) although it is an immediate CO_2 loss for the stand harvested (Figure 7b).

   The greatest sustainable harvest of wood—and so greatest CO_2 savings in products and wood energy—would occur when the target harvest age is at the culmination of the mean annual increment (Figure 9a). Forest carbon also reaches an inflection of greatest storage rate, although a few decades
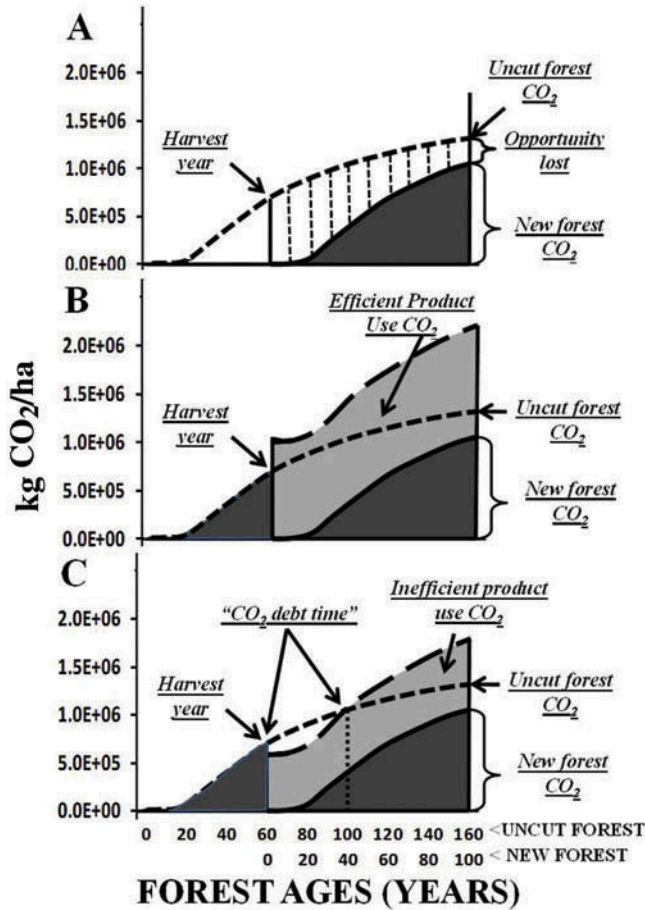
FIGURE 8 Tradeoffs and synergies of sequestering carbon in forests and products when forest growth is included in the analysis: (a) unharvested forest sequesters less carbon with older age, so regrowth can sequester increasingly larger parts of the CO_2 loss over time; (b) efficient wood use (gray) will immediately sequester more carbon than standing forest (black), and more will be sequestered as forest regrows (black); (c) inefficient wood use (e.g., wood energy) that saves only part of the CO_2 in the harvested stand will eventually sequester more CO_2 in the combination of regrowing forest (black) and products (gray) as a "dividend" following a "debt" period.

after wood growth. Sustainable, total carbon storage would be greatest when the sum of harvest and forest carbon were highest.

The shape of the MAI curve (Figure 9a) and consequently the time of greatest CO_2 savings in the combination of products, wood energy, and forest would vary with site, species, and silvicultural practices. The greatest CO_2 stored in the combination of products, and wood energy, and forest can be determined for each forest management regime; and development of optimum harvest for CO_2 savings could be further refined to ensure all structures are maintained (Hennigar et al., 2008; Oliver et al., 2009). In addition, the
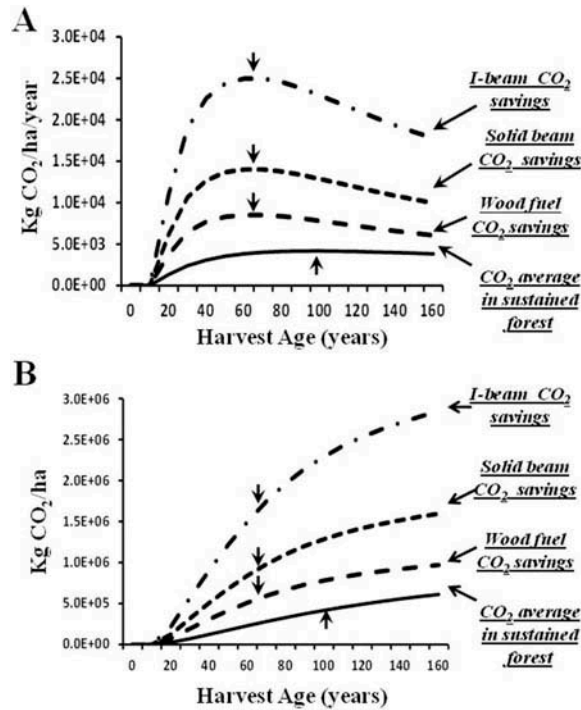
FIGURE 9 Effects of sustainability—growth equals harvest—on total forest and product CO_2 savings. Forest carbon is average of all stands in landscape. (a) Sustainability—growth equals harvest—can be achieved at different rates of CO_2 storage in products and forest (and different FF savings) by harvesting at different ages because average volume growth and carbon storage change with target harvest age. Arrows show maximum rates of forest growth ("culmination of mean annual increment") and forest carbon storage. (b) Total annual CO_2 storage in sustainable forests is the sum of the forest landscape carbon and CO_2 saved by products. Since forest and product carbon are not maximized at same harvest age, optimum storage would be at an intermediate harvest age. (CO_2 values and ages would vary with species, productivity, and management.)

likelihood of the forest burning in a catastrophic fire can be determined and specific silvicultural operations can be taken to reduce the fire danger.

DISCUSSION AND CONCLUSIONS

Globally, both enough extra wood can be harvested sustainably and enough infrastructure of buildings and bridges needs to be built to reduce annual CO_2 emissions by 14 to 31% and FF consumption by 12 to 19% if part of this infrastructure were made of wood. The range is based on the efficiency of wood use (Figure 6b–c). This reduction would require 34 to 100% of the world's wood growth (Figure 6a), again depending on the efficiency

of wood use. Consequently, efficient wood use could make an important but not overwhelming contribution to saving CO_2 and FF globally, even if only part of its potential savings were realized. The greatest CO_2 and FF savings from wood use are by avoiding the excess FF energy used to make steel and concrete structures (avoidance pathway). Wood products are more efficient than wood energy for CO_2 and FF savings; however, up to 37 % of the world's annual CO_2 emissions and 27% of the FF use could be saved if all wood growth not used in construction were used for energy (energy pathway; Figure 6b–c).

If catastrophic fires do not occur and forest regrowth after harvest is not considered, saving CO_2 by not harvesting the forest growth is slightly more efficient than harvesting just for wood energy—but generally less efficient than harvesting for construction products. This efficiency of CO_2 storage in unharvested forests also assumes none of the wood blows over or otherwise rots in the forest—an unrealistic assumption in most of the world.

Not harvesting any of an area's forests will also not gain maximum biodiversity if all stands grow out of the savanna and open structures (Figure 2 & Table 5). Maximum forest carbon will not create maximum biodiversity since savanna, open, and dense structures sequester less CO_2 than understory and complex ones. A forest needs either fortuitous disturbances occurring at the right time and place or it needs appropriate harvesting to maintain all structures. Wood harvested to create the open and savanna structures can be used for construction products and wood energy and to reduce the likelihood of catastrophic fires—all of which save CO_2 and FF.

When regrowth after harvest is considered, even wood harvested just for energy (energy pathway) can be more efficient for CO_2 sequestration than not harvesting the forest and using FF for energy. By elaborating the sustained yield calculations, it is possible to design dynamic, sustainable landscapes that maintain all structures for habitat, provide wood sustainably at an age that optimizes CO_2 savings (mean annual increment, Figure 9A), and makes the forest less susceptible to catastrophic fires. Included in these landscapes could be some forests that are reserved from harvest to provide complex structures (Seymour & Hunter, 1999)—although they could reduce the potential CO_2 and FF saved had they been appropriately harvested and utilized.

Immediately changing to older harvest ages to save more CO_2 (Figure 9) could delay all wood harvest where older forests are not present. Such delays could lead to temporary, local timber shortages that might promote more CO_2-intensive steel and concrete products. A "transition" period could be instituted to avoid these temporary shortages. On the other hand, the world's excess wood growth relative to harvest means the extra wood needed while waiting for young forests to grow could probably be obtained quite readily from elsewhere.

It may be appropriate to adjust carbon sequestration incentives and building codes to reflect the value of wood use in saving CO_2 and FF (Ruddell et al., 2007). For example, REDD and other incentives that seek to store CO_2 in forests appear to be counterproductive if curtailing harvest meant steel and concrete were used in construction instead, with concomitant high rates of CO_2 emissions and FF consumption. A dilemma becomes how to avoid deforestation and degradation while promoting CO_2 savings if wood products/wood energy save much CO_2. One solution would be to credit landowners for additional CO_2 stored in the forest at a landscape level, but give CO_2 credits to builders for substituting wood for steel or concrete construction components (Figure 1; mgb Architecture + Design, 2012). It is anticipated that the builder would pass some of the money saved by using wood to the landowner in increased timber prices. The result would be incentives for landowners to grow useful forest products/wood energy, but also to store more carbon within the forest landscape. Such a solution could be further enhanced by only allowing REDD, other forest carbon credits, and/or wood construction carbon incentives where wood is harvested from certified forests, presuming certification ensures that forests are sustained and biodiversity is protected.

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