Climatic Change
DOI 10.1007/s10584-012-0624-0

Carbon sequestration via wood harvest and storage: An assessment of its harvest potential

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Received: 10 August 2011 / Accepted: 29 October 2012

Abstract A carbon sequestration strategy has recently been proposed in which a forest is actively managed, and a fraction of the wood is selectively harvested and stored to prevent decomposition. The forest serves as a 'carbon scrubber' or 'carbon remover' that provides continuous sequestration (negative emissions). Earlier estimates of the theoretical potential of wood harvest and storage (WHS) based on coarse wood production rates were 10 ± 5 GtC y^{-1}. Starting from this physical limit, here we apply a number of practical constraints: (1) land not available due to agriculture; (2) forest set aside as protected areas, assuming 50 % in the tropics and 20 % in temperate and boreal forests; (3) forests difficult to access due to steep terrain; (4) wood use for other purposes such as timber and paper. This 'top-down' approach yields a WHS potential 2.8 GtC y^{-1}. Alternatively, a 'bottom-up' approach, assuming more efficient wood use without increasing harvest, finds 0.1–0.5 GtC y^{-1} available for carbon sequestration. We suggest a range of 1–3 GtC y^{-1} carbon sequestration potential if major effort is made to expand managed forests and/or to increase harvest intensity. The implementation of such a scheme at our estimated lower value of 1 GtC y^{-1} would imply a doubling of the current world wood

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Published online: 13 November 2012

harvest rate. This can be achieved by harvesting wood at a moderate harvesting intensity of 1.2 tC ha^{-1} y^{-1}, over a forest area of 8 Mkm^2 (800 Mha). To achieve the higher value of 3 GtC y^{-1}, forests need to be managed this way on half of the world's forested land, or on a smaller area but with higher harvest intensity. We recommend WHS be considered part of the portfolio of climate mitigation and adaptation options that needs further research.

1 Climate mitigation and adaptation: An important role for biospheric carbon sequestration?

Atmospheric CO_2 concentration has increased from a pre-industrial value of 280 ppm to nearly 390 ppm today, mostly due to carbon emissions from fossil-fuel burning and deforestation. The stated goal of the United Nations Framework Convention on Climate Change (UNFCCC) is to stabilize greenhouse gas concentrations at a level that would prevent 'dangerous anthropogenic interference with the climate system'. With the approval of the Copenhagen Accord, signatory nations recognized a goal of limiting global warming to below 2 °C. Achieving this goal will require ambitious action on a very large scale. The International Energy Agency (IEA 2009), for example, found that a 450 ppm stabilization scenario thought to be consistent with the 2 °C goal would require an investment of 10 trillion US dollars over the next 20 years with an effective carbon price of US \$50–\$110/tCO_2 (metric tonnes of carbon dioxide), and up to \$1,000/tCO_2 toward the end of the century.

The primary pathway to reduced greenhouse gas emissions is a transition to "low carbon economies," in which energy efficiency is improved and energy production has a much lower carbon footprint by transforming the energy infrastructure to include more renewable technologies and carbon capture and sequestration. Such a transition, however, is quite difficult to accomplish at the rate required to limit global temperature rise of 2 °C—the switch to low-carbon infrastructure is a slow process due to a variety of technological, socioeconomic, and political barriers. Thus carbon sequestration, namely capturing carbon that is already in the atmosphere and locking it away, could play an important role in the cost-effective stabilization of atmospheric CO_2 at acceptable levels. Negative emissions may also be needed in light of the long lifetime of atmospheric CO_2 even after emissions are completely stopped. Indeed, nearly all future emissions scenarios that involve policy-intervention assume significant contribution from carbon sequestration (IEA 2009; Pacala and Socolow 2004; Stern 2007), in particular, carbon capture and storage in geological formations (CCS) (IPCC 2005).

The removal of CO_2 from the atmosphere can utilize physical, chemical or biological methods (Royal Society 2009). Biological carbon sequestration, hereafter biosequestration, relies on plant photosynthesis to capture CO_2 and assimilate the carbon into biomass. Examples of biosequestration include reforestation, no-till agriculture, and intensive forest management (IPCC 2000). In one of the earliest studies on climate mitigation, Freeman Dyson (Dyson 1977; Dyson and Marland 1979) estimated that planting fast-growing trees on an area approximately the size of the United States would be enough to offset 5 GtC y^{-1} (Giga tonne carbon per year) of fossil fuel emissions (FFE). Afforestation or reforestation is arguably the most widely embraced carbon sequestration technique because of its low cost, benign nature and many co-benefits. Unfortunately, its capacity is limited by the availability of land and the sink slows down as the forest matures. Because fossil fuel emissions from energy production continue to increase beyond the sequestration capacity of terrestrial ecosystems, mitigation through land-use management is usually viewed as a low-cost approach with relatively modest total mitigation potential.

The greatest potential for biosequestration may not come from one-time carbon storage in live biomass, but from using plants as a 'carbon scrubber'. For example, despite the attractiveness of reforestation, the carbon sink diminishes as a forest matures. An alternative is to manage a forest in a way to separate 'carbon removal' via photosynthesis from 'carbon storage'. We can siphon off a fraction of the large biospheric productivity and store it away semi-permanently, thus creating a continuous stream of carbon sink (Fig. 1). If our active management stores, say 3 GtC y^{-1}, or 5 % of the terrestrial NPP, we can absorb more than 1/3 of current fossil fuel CO_2 emissions. Such reasoning lies behind recent estimates of large (theoretical) biosequestration or bioenergy potential through forestry and agriculture (Jansson et al. 2010; Lehmann et al. 2006; Lenton 2010; Read 2008; Strand and Benford 2009; Zeng 2008).

2 Wood harvest and storage (WHS) for carbon sequestration

A biological carbon sequestration strategy, hereafter termed Wood Harvest and Storage (WHS) has recently been proposed in which forest is actively managed, and a fraction of the wood is selectively harvested via collection of dead wood or selective cutting of less productive trees, and the logs are buried or stored above-ground to prevent decomposition (Zeng 2008). Related biosequestration ideas include no-till agriculture (Lal 2003), mixing biochar in soil (Woolf et al. 2010), sinking agricultural waste into the ocean (Metzger and Benford 2001; Strand and Benford 2009) and burying logs in abandoned mines (Scholz and Hasse 2008). Compared to many traditional carbon management ideas in which the stored carbon saturates after a period of time, WHS creates a continuous stream of sequestered carbon. Carbon in stored wood would be relatively easy to monitor and verify, reducing risk of loss and other issues facing some other carbon sequestration strategies.

However, a number of issues need to be addressed. The strategy must be evaluated quantitatively before its place in the portfolio of carbon sequestration strategies can be assessed. Among the most urgent questions is the potential of WHS given a number of known constraints, especially in light of competing land use. An earlier estimate of a theoretical potential 10±5 GtC y^{-1} was based on 'potential' coarse wood production rate, assuming natural vegetation in the absence of human activities (Zeng 2008). While this was a useful exercise both to define the strategy and estimate a maximum potential, the presence

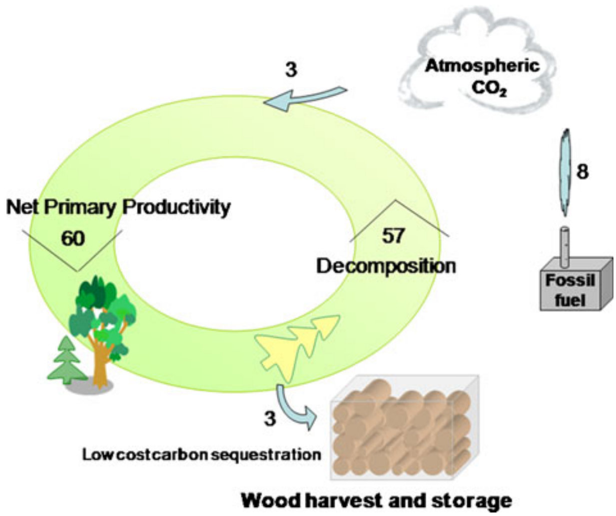


Fig. 1 Schematic diagram of carbon sequestration via wood harvest and storage (WHS). In this example, siphoning off 3 GtC y^{-1}, or 5 % of the terrestrial NPP in the form of wood logs in semi-permanent storage below or above ground can counter a significant fraction of the fossil fuel CO_2 emissions. This work estimates a carbon sequestration potential between 1–3 GtC y^{-1}. Numbers indicate carbon fluxes in GtC y^{-1}

of human activities and the modification of natural vegetation, especially clearing of forest for agriculture, can not be ignored, and these and other constraints will limit the potential of WHS to only a fraction of its theoretical potential. Here we address a number of such constraints globally and regionally in Section 3. A second set of questions associated with implementation and possible constraints on the realization of even this limited harvest potential is beyond the scope and is therefore not addressed here. Discussion and Conclusions are in Section 4.

3 Estimating the harvest potential of WHS

Many technical, environmental and socioeconomic factors will limit how much carbon can be sequestered via WHS. For example, it will compete for land for other uses, most notably agriculture, forestry, and biofuels. There may also be competition for other uses of the harvested biomass, either as traditional wood products of paper and building material or as biofuel. There may be constraints generated by where and how to store large quantities of woody biomass for decades and centuries. The environmental and social impacts of large-scale land management need to be carefully evaluated, and the economics of WHS or any other carbon sequestration strategy is inextricably linked to the price for carbon—how much is a ton of sequestered carbon worth. The higher the price of carbon, the less limiting are the costs of WHS. Some of these constraints, especially those associated with implementation, cannot be easily assessed at present, and are beyond the scope of the current exercise. Here we primarily limit ourselves to consideration of constraints on how much wood is available for WHS. We proceed with the rationale that if the potential is sufficiently high to compare favorably with alternative strategies, the additional effort to quantitatively evaluate the additional constraints is justified. Conversely, if that potential is comparatively small, additional constraints simply exacerbate the limited potential and further analysis is not needed.

Here we consider four major constraints on how much wood is available for WHS:

(1) Land not available for forestry due to the use for cropland and grazing pasture land;
(2) Forest land set aside as protected areas for biological diversity;
(3) Lack of accessibility due to technical difficulty and higher cost associated with steep terrain;
(4) Wood use for other consumer purposes such as timber and paper.

We evaluate these constraints from two perspectives. In the first, a 'top-down' approach, we estimate a maximum theoretical potential and then consider constraints on that potential to arrive at a potential necessarily less than (or equal to) the theoretical potential. In the second, a 'bottom-up' approach, we assume current global wood production reflects to a first approximation many of the constraints on how much wood could be produced. We then consider how much current wood production might reasonably be expanded as expanded harvest intensity or harvesting area under the additional incentive of climate mitigation to arrive at an estimate of the potential of WHS.

3.1 A 'top-down' estimate

The theoretical potential is estimated as coarse wood production rate under the condition of no human presence but with present climate and CO_2, i.e., 'potential vegetation'. We used the current version of the global dynamic vegetation and terrestrial carbon model VEGAS (Zeng 2003; Zeng et al. 2005). The carbon model was run to equilibrium forced by climate, and the results from the last 10 years of the simulation were analyzed. The results yield a global coarse wood production rate about 10 GtC y^{-1}, similar to an early version of the model (Zeng 2008). This global rate consists of 5.6 GtC y^{-1} from the tropics, 3.3 GtC y^{-1} from the temperate forests, and 1.1 GtC y^{-1} from the boreal forests (Table 1 and Fig. 2). Thus, tropical regions have significantly larger potential compared to temperate and boreal regions (Table 2 and Fig. 3). The fact that boreal region has relatively small potential may be counter intuitive in light of large expanses of boreal forests, but the productivity is smaller because of the temperature limited growth rate. In contrast, tropical forests have vigorous growth all year round wherever water is abundant.

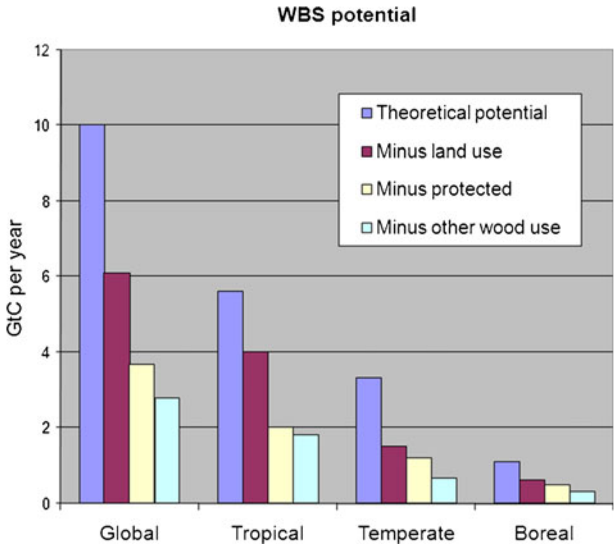
For the constraint from land use, we use the current land use pattern, while recognizing that future land use may change significantly in response to the need to feed increasing population, climate change policy and conservation (Wise et al. 2009). A land use map (Goldewijk 2001) was used to mask out the potential vegetation in VEGAS. Cropland is found to reduce the global theoretical potential by1.8 GtC y^{-1}, while grazing pasture land reduces it by another 2.1 GtC y^{-1}. After subtracting these, only 6.1 GtC y^{-1} coarse wood is available, a reduction of 40 % from the theoretical potential (Table 1 and Fig. 2). The cropland constraint is largest in the temperate region, 0.9 compared to 0.5 GtC y^{-1} in the tropics, whereas the grazing pasture land constraint is larger in the tropics (1.1) than temperate forests (0.9).

Forest protection is influenced by many factors. World wide protected areas for biodiversity account for 11 % of the total forest land (FAO 2005), but the major intact forests are tropical rainforests such as in the Amazon and the Congo Basin that are only weakly protected. International efforts are underway to reduce deforestation in such regions, though major issues remain, including the longevity of the protected carbon in the live biomass. Here we assume a simple scenario in which 50 % of the forested land in the tropics, and 20 % in temperate and boreal regions is held in protection areas for biological diversity and ecosystem services. This is applied to the remaining forest land after subtracting current land use for cropping and grazing, not the theoretical potential. The result is an additional reduction of 2.4 GtC y^{-1}, so that the global potential is now 3.7 GtC y^{-1}.

Table 1 Carbon sequestration potential via WHS (GtC y^{-1}), estimated with a 'top-down' approach as a theoretical potential minus successive constraints. Numbers in parentheses indicate the reduced potential due to the specific constraint. Boldface indicates the estimated final potential as limited by these constraints, and this potential as percentage of fossil fuel emissions in 2005 (FFE) (Boden et al. 2011). Also listed is the estimated area needed for WHS to achieve the corresponding carbon sequestration potential at moderate wood harvest intensity of 1.2 tC ha^{-1} y^{-1}

	Global	Tropics	Temperate	Boreal
Theoretical potential (GtC y^{-1})	10	5.6	3.3	1.1
-Cropland	8.2 (−1.8)	5.1 (−0.5)	2.4 (−0.9)	0.7 (−0.4)
-Grazing pasture land	6.1 (−2.1)	4.0 (−1.1)	1.5 (−0.9)	0.6 (−0.1)
-Protected (50 % Trop, 20 % temperate/boreal)	3.7 (−2.4)	2 (−2)	1.2 (−0.3)	0.5 (−0.1)
-Other wood use (FAO 2005)	**2.8** (−0.9)	**1.8** (−0.2)	**0.7** (−0.5)	**0.3** (−0.2)
=>**Constrained potential** (GtC y^{-1})				
Regional potential as percentage of global total WHS potential	100 %	64 %	25 %	11 %
Area needed for WHS to achieve the above potential (million km^2)	24.6	10.9	8.0	5.7
Fossil fuel emissions (FFE) 2005 (GtC y^{-1})	8	1	6	1
WHS potential as percentage of FFE	**35 %**	**182 %**	**11 %**	**30 %**

Fig. 2 Carbon sequestration potential in global, tropical, temperate and boreal forests in GtC y^{-1}. Theoretical potential is reduced by successive constraints on forest availability due to land use for cropping and grazing, protected area for biodiversity, and other wood use. The final values after subtracting wood use are the estimated potential, globally at 2.8 GtC y^{-1}. The numbers in the subsequent figures are consistent with this global value



Because steep terrain is generally difficult for access and forestry operations, the cost of WHS in steep areas will likely be too high. We used the 1 km digital elevation map GTOPO30/HYDRO1k from the US Geological Survey (http://gcmd.nasa.gov/records/GCMD_HYDRO1k.html) to calculate the topographic gradient and computed the average in each model grid point of VEGAS. We explored two scenarios, one in which area is considered not suitable for harvesting if average topographic gradient is larger than 6°, and another in which the gradient is larger than 3°. It turns out that the area with gradient larger than 6° falls completely within the biodiversity protected area defined using the scenario above, while the 3° gradient scenario includes about the same forest from the protection scenario for the temperate zone, while it is less for the tropical forests. Additionally, we assume protected areas overlap with steep terrain where it exists. As a result, we consider the terrain limit completely included in the protection scenario, and no further reduction for the harvesting potential is applied. This is an optimistic estimate because not all steep regions are preserved, but it is good approximation in light of the much larger uncertainty in other factors such as coarse wood production rate.

Finally, current world wood harvest for timber, paper and other products contains 0.9 GtC y^{-1}, including both industrial roundwood and fuel wood (FAO 2005), which we adopt as the wood use rate for our analysis. In reality, future wood use may increase, and the mix of uses may change. For instance, post-consumer wood products have already been partly utilized for energy through incineration (in replacement of fossil fuel) or buried in landfills semi-permanently (Micales and Skog 1997; Skog 2008), and it is generally expected that such usage will be more wide spread in the future. This current use is mostly in the temperate regions, especially in Europe where much of the wood productivity is already utilized.

After subtracting the forest wood productivity not available due to the above constraints, we obtain a wood harvest potential for carbon sequestration of 2.8 GtC y^{-1} globally, with contribution from tropical forests of 1.8 (64 %), temperate 0.7 (25 %) and boreal 0.3 GtC y^{-1} (11 %) (Table 1). Regionally, the potential is high in the tropics: South America could sequester 0.9 GtC y^{-1} or 32 % of the world total, while Africa can contribute 0.5 (21 %), Asia 0.42 (16 %), North America 0.32 (12 %), Oceania 0.28 (10 %), and Europe (including Russia) 0.23 (8 %) (Table 2). At the country level, while tropical rainforest countries in South America, Africa, Southeast Asia and Oceania have large potential, some large

Table 2 As in Table 1, but for six main sub-regions of the world. The classification of these regions follows that of FAO (2005), in which Europe includes Russia, Oceania includes Indonesia, Australia and New Zealand, North America includes North and Central America and the Caribbeans

	Africa	Asia	Europe	North America	South America	Oceania
Theoretical potential (GtC y^{-1})	2.53	1.57	1.14	1.17	2.78	0.87
-Land use (crop+pasture)	1.58 (−0.95)	0.65 (−0.92)	0.52 (−0.62)	0.7 (−0.47)	2.05 (−0.73)	0.6 (−0.27)
-Protected (50 % Tropics, 20 % temperate/boreal)	0.79 (−0.79)	0.52 (−0.13)	0.42 (−0.1)	0.56 (−0.14)	1.03 (−1.02)	0.3 (−0.3)
-Other wood use	**0.57** (−0.22)	**0.42** (−0.1)	**0.23** (−0.19)	**0.32** (−0.24)	**0.9** (−0.13)	**0.28** (−0.02)
=>**Constrained potential** (GtC y^{-1})						
Country/region potential as percentage of global total WHS potential	21 %	16 %	8 %	11 %	32 %	10 %
Area needed for WHS to achieve the above potential (Mkm^2)	4.0	4.2	4.2	4.7	5.5	2.0
FFE 2005 (GtC y^{-1})	0.25	3.3	1.5	1.9	0.3	0.2
WHS potential as percentage of FFE	**228 %**	**13 %**	**15 %**	**17 %**	**300 %**	**140 %**

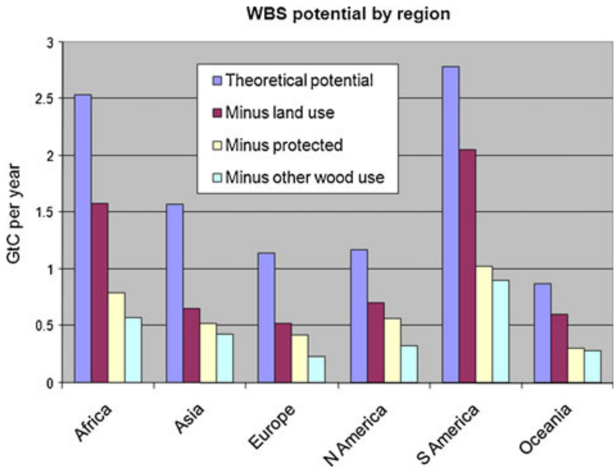


Fig. 3 As in Fig. 2, but for six main world regions

temperate and boreal countries can also be significant contributors, including the US for 0.14 GtC y^{-1} (5 % of world total), Canada 0.09 (3 %), Russia 0.2 (7 %), China 0.14 (5 %), and Southeast Asia 0.28 (10 %) (Table 3).

We also computed the forest area needed to achieve the corresponding carbon sequestration potential. This was done by simply excluding land use, protected areas for biodiversity and wood use (using the above data or scenarios) from the VEGAS model simulated forest area. The global total area available for WHS is 24.6 million km^2 (Mkm^2, Table 1), about half of the total world forest area. Tropical forests account for 10.9 Mkm^2, temperate forests for 8 Mkm^2, and boreal forests for 5.7 Mkm^2. It is interesting to compare area needed with carbon sequestration potential. For instance, tropical WHS potential is 1.82 GtC y^{-1}, 6 times as large as the 0.3 GtC y^{-1} potential for boreal forests, but it needs only twice as much forest area as in the boreal region, reflecting the high productivity of tropical forests.

Our estimated WHS potential of 2.8 GtC y^{-1} is a significant amount compared to the fossil fuel emissions of 8 GtC y^{-1} (for the year 2005), and the current deforestation emissions of 1.2±0.6 GtC y^{-1} (van der Werf et al. 2009). However, major uncertainties exist in our knowledge of the potential wood production rate and the various technical constraints, human activities and choices. For instance, a land owner may simply choose not to conduct harvesting in his/her forests, regardless of the income, especially for small land parcels from which the financial return would be too small in absolute terms. Our estimate also assumed no disturbance to the remaining forests. In the boreal forest region, global warming induced thawing is making the traditional winter roads more difficult and costly to access. The estimate does not, for example, include future changes in either forest productivity or the forested land base. Continued deforestation pressure in the tropics could reduce the latter. Elevated atmospheric CO_2, even assuming stabilization at 450 ppm, could increase forest productivity. Climate change, even with a global increase in temperature limited to less than 2 °C, could increase forest productivity in some areas and decrease it in others.

3.2 A 'bottom-up' estimate

We now turn to a 'bottom-up' perspective on the potential of WHS. We assume current roundwood harvest and subsequent long term storage as a proxy for WHS potential constrained, to first approximation, by land availability, forest productivity, cost of

Table 3 As in Table 1, but for a few selected countries and region

	US	Canada	EU27	Russia	China	Southeast Asia
Theoretical potential (GtC y^{-1})	0.73	0.21	0.5	0.61	0.72	0.8
-Land use	0.38 (−0.35)	0.17 (−0.04)	0.21 (−0.29)	0.3 (−0.31)	0.23 (−0.49)	0.66 (−0.14)
-Protected (50 % Tropics, 20 % temperate/boreal)	0.3 (−0.08)	0.14 (−0.03)	0.17 (−0.04)	0.24 (−0.06)	0.18 (−0.05)	0.33 (−0.33)
-Other wood use	**0.14** (−0.16)	**0.09** (−0.05)	**0.05** (−0.12)	**0.2** (−0.04)	**0.14** (−0.04)	**0.28** (−0.05)
=>**Constrained potential** (GtC y^{-1})						
Country/region potential as percentage of global total WHS potential	5 %	3 %	2 %	7 %	5 %	10 %
Area needed for WHS to achieve the above potential (Mkm^2)	2.0	2.0	1.1	4.0	2.0	1.4
FFE 2005 (GtC y^{-1})	1.59	0.15	1.1	0.41	1.53	0.45
WHS potential as percentage of FFE	**9 %**	**57 %**	**5 %**	**49 %**	**9 %**	**62 %**

extraction, etc. Approximately half of the current 0.9 GtC y^{-1} global wood harvest is industrial roundwood; the rest is fuelwood (FAO 2010). The fuelwood is consumed relatively quickly and most of the carbon returned to the atmosphere as CO_2. Carbon is also lost during processing and conversion of the industrial roundwood (Ingerson 2009), and the growing fraction of paper and wood-based panel products have relatively short half-lives (Winjum et al. 1998). Only about 25 % (20–30 %) of delivered wood harvest is sequestered in long-lived products or landfills (e.g., Winjum et al. 1998; Skog 2008; Ingerson 2009). We estimate accordingly that current global wood product sequestration is only on the order 0.1 GtC y^{-1} (0.9 GtC $y^{-1} \times 0.5 \times 0.25 = 0.1$ GtC y^{-1}). Winjum et al. (1998) estimated a comparable global sequestration in wood products of 0.139 GtC y^{-1} in 1990. Hashimoto et al. (Hashimoto et al. 2002) estimated a global sequestration in wood products of 0.217 GtC y^{-1} for the decade 1990–1999.

Reducing waste at timber harvest and in the processing of wood products, combined with management to reduce the burning and decay of wood products in and outside of landfills, could increase current wood product sequestration. Similarly, a shift in demand for fuelwood to alternative non-fossil energy sources such as solar and wind could make more of the total wood harvest available for WHS. Reduction in the demand for paper products could also make more of the industrial roundwood harvest available for sequestration. Allowing, speculatively, for an increase of up to 5-fold through these mechanisms leads to an estimate of WHS potential of 0.5 GtC y^{-1}. Note that this would require utilizing part of the harvest loss which is at least 30 % more than the 0.9 GtC y^{-1} (FAO 2005). This range of 0.1–0.5 GtC y^{-1} is consistent with an independent estimate of 0.33 GtC y^{-1} (Lenton 2010), based on the simple assumption that present forest harvest felling loss can all be buried.

One of Pacala and Socolow's (2004) "stabilization wedges" amounts to 1 GtC y^{-1} in 2054. Achieving this target for credible consideration as a mitigation strategy implies a 10-fold increase in current rates of carbon sequestration in long-lived wood products and burial in landfills. Again, achieving even this more modest goal (a 10 times increase rather than 30 times) seems to us unlikely through increases in efficiency, wood product management and energy substitution alone. An increase in wood harvest would likely be required. If we assume, unrealistically, but for the purpose of argument, perfect efficiency (zero carbon loss) during the processing of wood product and long-lived sequestration (minimal decay) of all wood products, the target of 1 GtC y^{-1} could be achieved by a doubling of the approximately 1 GtC y^{-1} global wood harvest (recall that approximately half of that harvest is consumed as fuelwood). This doubling could be achieved by harvesting wood at a harvesting intensity of 1.2 tC ha^{-1} y^{-1}, over a forest area of 8 Mkm^2 (800 Mha). Shifts of fuelwood demand to non-fossil energy sources would allow for some loss of carbon during processing and in the decay of wood products. Alternatively a doubling of wood harvest assuming the current demand of approximately 50 % of that harvest for fuelwood and the current allocation of industrial roundwood to various short and long-lived wood products (including burial in landfills) results in a estimated sequestration of only 0.2 GtC y^{-1}. Nevertheless, on the assumption that some combination of increase in wood harvest, energy substitutes for fuelwood, management of waste during harvest and processing and management of carbon loss from the resulting wood products could realize a 10-fold increase in current rates of carbon sequestration in long-lived wood products, we set an upper bound on the bottom-up estimate of WHS potential of 1 GtC y^{-1}. Combining our top-down and bottom-up analyses we thus arrive at an estimate for the potential of WHS in the range of 1–3 GtC y^{-1}. This is in the middle of a 0.5–4 GtC y^{-1} range for a number of terrestrial carbon sequestration mechanisms estimated by Lenton ((Lenton 2010).

4 Discussion and conclusions

Using the coarse wood production rate of the world's forests and the constraints from land use, protected areas for biodiversity, accessibility, and other wood use in a top-down approach, we estimated a 2.8 GtC y^{-1} carbon sequestration potential with wood harvest and storage. A bottom-up approach based on a plausible expansion of the current world wood harvest rate yielded a 1 GtC y^{-1} sequestration potential with WHS. We thus estimate a range of 1–3 GtC y^{-1} sequestration potential with WHS.

The implementation of such a scheme at our estimated lower potential of 1 GtC y^{-1} would imply a doubling of the current world wood harvest rate, which can be realized at a moderate harvest intensity of 1.2 tC ha^{-1} y^{-1} over an area of 8 Mkm^2, and possibly a much smaller area with higher harvest intensity or fast growing plantations. Such an expansion would be a giant leap for traditional forestry, but it is not inconceivable, and in fact possible in light of large potential impacts of climate change, including those on forests themselves, and the high cost of CO_2 reduction by other means.

There will be a broad range of technical, environmental, and socioeconomic issues. Our estimates of carbon sequestration potential do not yet take into account many such constraints because the limited available information. A number of potential issues of managing forests for WHS were discussed by Zeng (2008), including nutrient loss, disturbance to the forest floor, biodiversity, cost, lifetime of stored wood, and unintended consequences. Thus, many tradeoffs of such forest management schemes need to be carefully evaluated. One possible issue of 'carbon debt' has been highlighted recently in which the initial carbon loss from forest conversion for biofuel production would take a long-time to be 'repaid' by the benefits (Fargione et al. 2008). In WHS, forest is maintained so one can expect much less carbon loss but careful management and monitoring are essential. Most of these issues will need significant research and experimentation. Many of these issues are not unique to WHS, but are encountered in forest management in general and more broadly in climate mitigation and adaptation. While there have been many examples of irresponsible logging in the past, best forest management practices have been increasingly used with minimum negative environmental consequences. It is also important to recognize that WHS for carbon sequestration is merely one more option to the existing suite of forest management and product use choices (Ryan et al. 2010), but it nonetheless adds a new dimension to the portfolio. This new use of wood will likely reshape the current timber market. It is critically important to devise strategies that will maximize the overall socioeconomic, environmental and climate benefits while minimizing any potential downsides.

We know of no wood harvest and storage operation as envisioned here that has been conducted purposefully for long-term carbon sequestration. Because it does not involve truly unproven technology, we argue that WHS is sufficiently promising to warrant more evaluation and testing of its feasibility and sustainability as a climate mitigation and adaptation strategy.

Acknowledgments We are grateful for discussion and critiques from Gregg Marland, Lianhong Gu, Brian Cook, Peter Read, Ross Salawitch, Steve Smith, Cesar Izzaraulde, Dalia Abbas, Richard Birdsey, Linda Heath, Yude Pan, Ben Bond-Lamberty, Tris West, Brent Sohngen, Tony Janetos, Fritz Scholz, George Hurtt, Ruth DeFries, Thomas Schelling, Freeman Dyson, Paul Crutzen, Graham Stinson, Neil Sampson, Ruben Lubowski, Alexander Golub, Matt Pearson, Roger Sedjo, Steven Hamburg, and Ian Noble. This work resulted in part from a workshop entitled "Ecological carbon sequestration via wood burial and storage: A strategy for climate mitigation and adaptation", held at the Heinz Center, Washington DC during September 9–10, 2010. This work was supported by NSF grant AGS-1129088, and NOAA grant NA10OAR4310248. AWK and SDW acknowledge support from the U.S. Department of Energy (DOE), Office of Science, Biological and Environmental Research (BER) program. Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for the DOE under contract DE-AC05-00OR22725.

References

Boden TA, Marland G, Andres RJ (2011) Global, regional, and national fossil-fuel CO2 emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A

Dyson FJ (1977) Can we control the carbon dioxide in the atmosphere? Energy 2:287–291

Dyson FJ, Marland G (1979) Technical fixes for the climatic effects of CO2. In: Elliott WP, Machta L (eds) Carbon Dioxide Effects Research and Assessment Program, Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels, US Department of Energy.

FAO (2005) The global forest resources assessment 2005. Food and Agriculture Organization of the United Nations, Rome, p 350

FAO (2010) The global forest resources assessment 2010. Food and Agriculture Organization of the United Nations, Rome, p 340

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. Science 319:1235–1238

Goldewijk KK (2001) Estimating global land use change over the past 300 years: the HYDE database. Global Biogeochem Cycles 15:417–433

Hashimoto S, Noseb M, Obarac T, Moriguchi Y (2002) Wood products: potential carbon sequestration and impact on net carbon emissions of industrialized countries. Environ Sci Pol 5:183–193

IEA (2009) World energy outlook 2009 edition - climate change excerpt. International Energy Agency, Paris, p 62

Ingerson A (2009) Wood products and carbon storage: can increased production help solve the climate crisis? Wilderness Society, Washington, D.C., p 47

IPCC (2000) Special report on land use, land-use change and forestry. Cambridge University Press.

IPCC (2005) Special report: carbon dioxide capture and storage. Cambridge University Press.

Jansson C, Wullschleger SD, Kalluri UC, Tuskan GA (2010) Phytosequestration: carbon biosequestration by plants and the prospects of genetic engineering. Bioscience 60:685–696

Lal R (2003) Global potential of soil carbon sequestration to mitigate the greenhouse effect. Crit Rev Plant Sci 22:151–184

Lehmann J, Gaunt J, Rondon M (2006) Bio-char sequestration in terrestrial ecosystems-a review. Mitig Adapt Strateg Glob Chang 11:403–427

Lenton TM (2010) The potential for land-based biological CO2 removal to lower future atmospheric CO2 concentration. Carbon Manag 1:145–160

Metzger RA, Benford G (2001) Sequestering of atmospheric carbon through permanent disposal of crop residue. Clim Chang 49:11–19

Micales JA, Skog KE (1997) The decomposition of forest products in landfills. Int Biodeterior Biodegrad 39:145–158

Pacala S, Socolow R (2004) Stabilization wedges: solving the climate problem for the next 50 years with current technologies. Science 305:968–972

Read P (2008) Biosphere carbon stock management: addressing the threat of abrupt climate change in the next few decades: an editorial essay. Clim Chang 87:305–320

Royal Society (2009) Geoengineering the climate: science, governance and uncertainty. London.

Ryan MG, Harmon ME, Birdsey RA, Giardina CP, Heath LS, Houghton RA, Jackson RB, McKinley DC, Morrison JF, Murray BC, Pataki DE, Skog KE (2010) A synthesis of the science on forests and carbon for U.S. forests. Issues in Ecology, Washington, DC, p. 16.

Scholz F, Hasse U (2008) Permanent wood sequestration: the solution to the global carbon dioxide problem. Chemsuschem 1:381–384

Skog KE (2008) Sequestration of carbon in harvested wood products for the United States. For Prod J 58:56–72

Stern N (2007) The economics of climate change: the Stern review. Cambridge University Press, Cambridge, UK, p 692

Strand SE, Benford G (2009) Ocean sequestration of crop residue carbon: recycling fossil fuel carbon back to deep sediments. Environ Sci Technol 43:1000–1007

van der Werf GR, Morton DC, DeFries RS, Olivier JGJ, Kasibhatla PS, Jackson RB, Collatz GJ, Randerson JT (2009) CO2 emissions from forest loss. Nat Geosci 2:737–738

Winjum JK, Brown S, Schlamadinger B (1998) Forest harvests and wood products: sources and sinks of atmospheric carbon dioxide. For Sci 44:272–284

Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, Sands R, Smith SJ, Janetos A, Edmonds J (2009) Implications of limiting CO2 concentrations for land use and energy. Science 324:1183–1186

Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S (2010) Sustainable biochar to mitigate global climate change. Nat Commun 1.

Zeng N (2003) Glacial-interglacial atmospheric CO2 change - the glacial burial hypothesis. Adv Atmos Sci 20:677–693

Zeng N (2008) Carbon sequestration via wood burial. Carbon Balance Manag 3, 1.

Zeng N, Mariotti A, Wetzel P (2005) Terrestrial mechanisms of interannual CO2 variability. Glob Biogeochem Cycles 19.