STATUS AND POTENTIAL OF TERRESTRIAL CARBON SEQUESTRATION IN WEST VIRGINIA

Benktesh D. Sharma and Jingxin Wang[1]

Abstract.—Terrestrial ecosystem management offers cost-effective ways to enhance carbon (C) sequestration. This study utilized C stock and C sequestration in forest and agricultural lands, abandoned mine lands, and harvested wood products to estimate the net current annual C sequestration in West Virginia. Several management options within these components were simulated using a systems modeling approach to estimate C sequestration potentials. With such activities as substituting unused biomass resources for bioenergy production, converting marginal lands to forest covers, and extending the life of harvested wood products, atmospheric C sequestration by terrestrial ecosystems in West Virginia can be increased to 8.40 million t C/year from the current level of 5.50 million t C/year. These activities have the potential to provide additional benefits in terms of energy savings and CO_2 emission reduction at the source compared to other available carbon sequestration alternatives.

INTRODUCTION

Almost all of West Virginia consists of terrestrial ecosystems, and forest ecosystems alone cover more than 80 percent of terrestrial components (Fig. 1). Interest in atmospheric carbon (C) reduction through terrestrial ecosystem management is strong in West Virginia (as elsewhere) not only because of the prevalence of these ecosystems but also because of the cost-effectiveness of these components as a means of reducing atmospheric C compared to available alternatives. Managing these components requires knowledge about the limits of these ecosystem components' capacity to sequester atmospheric C and about the limiting factors of other components that directly affect such potentials. This paper describes the status and potential of C sequestration in terrestrial ecosystem components of forest lands, agricultural lands, mine lands, and harvested wood products (HWP) through different enhancement strategies along with limitations. Additionally, the paper compares the terrestrial ecosystem-based C sequestration options with other options on the basis of cost, feasibility, and efficiency of emission reduction in West Virginia.

METHODS

Estimates of forest C stock were obtained using Carbon On Line Estimator (COLE) available at http://ncasi.uml.edu/COLE/. Information on available mine lands, boundaries, and status was obtained from the West Virginia Department of Environmental Protection (2008). Information on C in harvested wood and applicable end uses was obtained from Timber Products Output data, available at http://nrs.fs.fed.us/fia/topics/tpo/. Energy production and C emission reduction through replacement of coal fuel with biomass for energy production were obtained from available conversion factors applicable for West Virginia (USDA, Forest Products Laboratory 2004, Wang and others 2007, Plant Fossils of West Virginia 2009).

[1]Graduate Research Assistant (BDS), and Associate Professor (JW), Division of Forestry and Natural Resources, West Virginia University, Morgantown, WV 26506. JW is corresponding author: to contact, call (304)293-7601 or email at jxwang@wvu.edu.

Carbon content in wood biomass was estimated as half of the total biomass (Eq. 1). The biomass content removed from the forest was obtained by using a volume-density relationship (USDA, Forest Products Laboratory 1953, Grantham and Ellis 1974, Smith 1991) for the different species (Eq. 2). Between 2000 and 2006, the ratio of net growth to removal (Eq. 3) in West Virginia forests was approximately 1.5 in terms of volume of growing stock (Sharma and others 2009, USDA, Forest Service 2009). This ratio implies that 40 percent of current growth is harvested and the remaining 60 percent remains standing. This ratio was even higher in previous years: 2.1 in 1994 and 2.0 in 1979 (Widmann and others 1998). This growth-to-removal ratio means that there will be two distinct pools of forest. One pool has a higher mean age and a

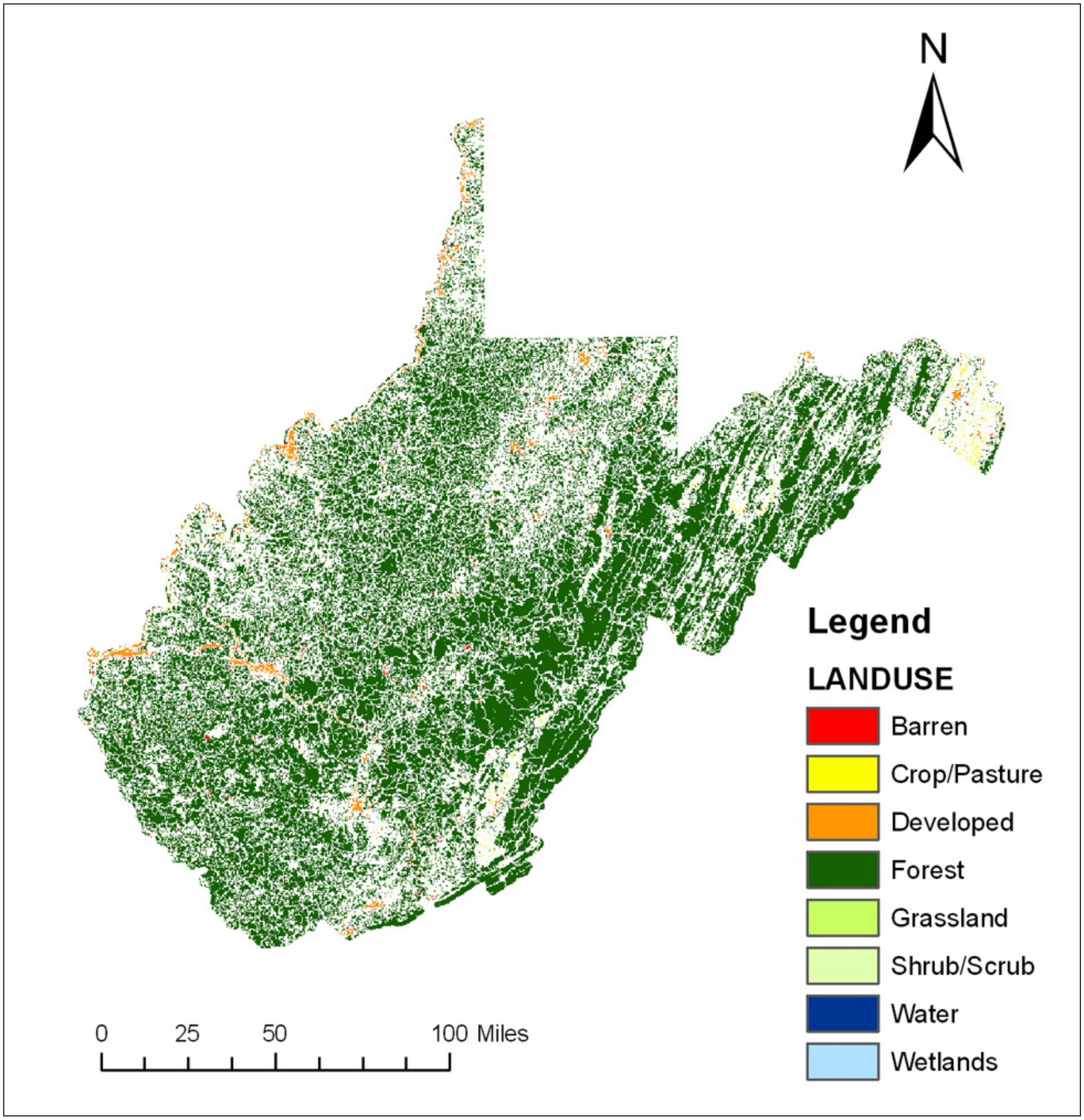

Figure 1.—Major land use in West Virginia (Data source: USGS NLCD 2001).

lower sequestration rate than the other pool. The mean C sequestration rate for the entire forest was obtained by proportionally applying two growth rates using Eq. (4) (Sharma 2010). These two growth rates were applied to capture the variations in growth rate inherent in the nonlinear growth characteristics of forests. A forest sequesters C at different rates along its life; initially, the rate is low, followed by rapid growth in the middle and finally a slower growth rate in old stands (Sharma 2010). Removal of C occurs when forests are harvested and this stock is estimated using Eq. (5) (derived from Eq. [3]). The harvested products emit C to the atmosphere through decomposition and decay and often go through several production stages during their lives. Depending on product use, these products have variable product life and a variable amount of C stored at different times. Amount of C remaining in a product was estimated from an exponential decay function with the half-life of C in the particular product type (Table 1) using Eq. (6). When harvesting occurs each year, the resulting annual value of C in harvested products can be estimated by using Eq. (7). Eq. (5) remains the parent equation for Eq. (6) and (7). C sequestered in agricultural lands and mine lands was obtained by using area and C sequestration rate. Total terrestrial sequestration was obtained by combining C sequestered in forests, agricultural lands, mine lands, and harvested wood product pools (Eq. 8).

$$B_c = 0.5\,B \tag{1}$$

$$B_s = V_{B_i} D_{B_i} \text{ for } i = 1\text{....species group} \tag{2}$$

$$GRR = \frac{ACA}{ACR} \tag{3}$$

$$ACA = A \frac{1}{GRR + 1}\ (GRR * r_1 + r_2)\} \tag{4}$$

$$AGR = \frac{ACA}{GRR} \tag{5}$$

$$Q_y = \Sigma_{\mathrm{n=1}}^{N}\ Q_n * [1 - \frac{1{:}\mathrm{n}(2)}{h_n}]^{(y-1)}\ \} \tag{6}$$

$$Q_y = \Sigma_{\mathrm{n=1}}^{N}\ Q_n * [1 - \frac{1{:}\mathrm{n}(2)}{h_n}]^{(y-1)} + \mathrm{c}\ \Sigma_{i=2}^{y}\ \Delta Q_n[1 - \frac{1\mathrm{n}(2)}{h_n}]^{(t-2)}\ \} \tag{7}$$

$$Tc = ACA + ACR + (A_{ag} - A_{mag}) * r_{ag} + A_{mag} * r_{agf} + r_{mlf} * AML \tag{8}$$

where B_c is carbon in removed forest biomass, B_s is biomass content in tons for species group s, V_{B_i} is volume of biomass removed in cubic feet from species group i, D_{B_i} is density of biomass removed from species group *i*, *GRR* is growth-to-removal ratio (> 0), *ACA* is annual C accrual (in million tons) in forest ecosystems, *A* is

Table 1.—Wood product half-life (years).

SN	Category	Half-life, years*	Applicable products
1	Long-term product	30	Saw logs; composite products
2	Medium-term product	15	Posts, poles, and pilings; veneer logs; fiber
3	Short-term product	1	Fuelwood; misc. products; pulpwood
4	Landfills	145	Discarded residues
5	Dump and let decay	5	Unused products

*Schelhaas and others 2004

total area of forests (in million acres), r_1 is C sequestration rate from forest growth (t C/acre) in old and over-mature stands, r_2 is C sequestration rate (t C/acre) in young to mature stands, *ACR* is annual carbon removed (million tons) from the forest ecosystem, Q_{t+1} is quantity of carbon at time y, Q_n is the initial quantity of carbon in the nth product, *Y* is number of years, *y* is any future time period between 1 and *Y*, *N* is number of different products from forest harvest, *n* is any product between 1 and ∞, h_n is expected half-life of product *n*, *t* is time period (year), ΔQ_n is the quantity of addition to previous stock in the nth category, *i* = 1...y where y ≥ 2, c = 0 if y < 2 and 1 otherwise, *Tc* is total terrestrial carbon, A_{ag} is area of agricultural lands, A_{mag} is area of marginal agricultural lands, r_{ag} is C sequestration rate in agricultural lands, r_{agf} is C sequestration rate in afforested marginal agricultural lands, A_{mi} is area of mine lands, and r_{ami} is C sequestration rate by afforestation in mine lands. Parameters used in the model were obtained from several sources and are listed in Table 2.

RESULTS

CARBON STOCK AND ANNUAL SEQUESTRATION

Twelve million acres of forest land in West Virginia store approximately 1,035 million tons of carbon in different ecosystem components; more than half of the total C is stored in standing live trees (Fig. 2). The state's hardwood forests store a majority of the total C (Table 3). These forests sequester C at the rate of 0.32 t C/acre (range 0.18-0.60 t C/acre) in harvested stands and at the rate of 0.21 t C/acre (range 0.05-0.29 t C/acre) in mature stands. The net annual C sequestration by these forests thus is about 3.9 million tons. These estimates represent the net accumulation of C after deduction due to mortality and emissions and are based on 200-year projections.

Table 2.—Definition of model parameters.

Parameter	Definition	Source
A	Area of forest land (million acres)	USGS NLCD (Homer and others 2004)
r_1	Forest C sequestration rate in old stands (t C/acre/year)	Sharma and others 2009, FVS model
r_2	Forest C sequestration rate in young stand (t C/acre/year)	Sharma and others 2009, FVS model
GRR	Growth-to-removal ratio	USDA-FS 2009
A_{ag}	Area of agricultural land (million acres)	USGS NLCD (Homer and others 2004), Niu and Duiker 2006
A_{mag}	Area of marginal agricultural lands (million acres)	Niu and Duiker 2006
r_{ag}	C sequestration rate in agricultural lands (t C/acre/year)	Sperow and others 2003
r_{agf}	Carbon sequestration rate in agricultural lands with afforestation (t C/acre/year)	Sperow and others 2003, Niu and Duiker 2006
AML	Area of abandoned mine lands (million acre)	WVDEP 2008
r_{am}	C sequestration in abandoned mine lands (t C/acre/year)	Sperow 2006
r_{mlf}	C sequestration in abandoned mine lands with afforestation (t C/acre/year)	Sperow 2006
V_{Bi}	Volume of biomass (m^3) in species i	TPO data,
D_{Bi}	Density of biomass (t/m^3) in species i	USDA-FPL 1953, Grantham and Eillis 1974, Smith 1991

Source: Sharma 2010

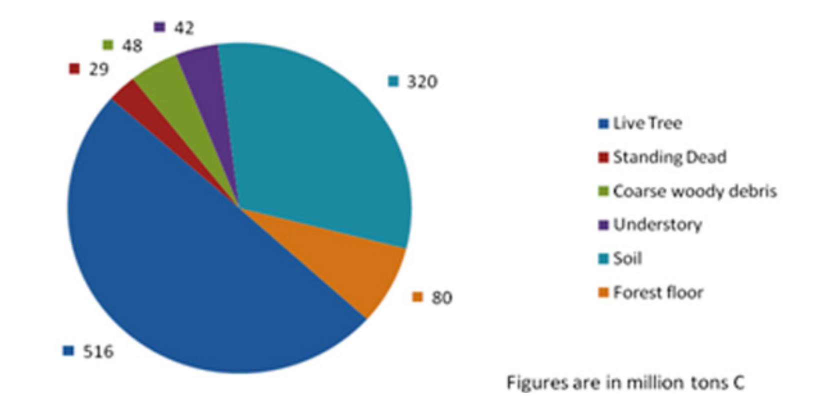

Figure 2.—Carbon storage in West Virginia forest ecosystem components (in million tons).

Table 3.—Amount of carbon (million t) stored in forests in West Virginia.

Forest type/group	t C/acre	Area (million acres)	Total (million t C)
Aspen/Birch Group	41.7	0.04	2
Elm/Ash/Cottonwood Group	108.36	0.04	4
Loblolly/Shortleaf Pine Group	72.88	0.04	3
Maple/Beech/Birch Group	95.91	3.91	375
Oak/Hickory Group	78.69	7.63	601
Oak/Pine Group	89.29	0.35	31
Spruce/Fir Group	88.31	0.02	2
White/Red/Jack Pine Group	89.05	0.08	7
All	85.23	12.12	1,035

Source: Carbon On Line Estimator (COLE)

Forest harvest in the state has remained constant at the rate of about 0.25 billion cubic feet per year. These removals are transformed into different wood products and do not include non-growing stock removals from thinning and silvicultural operations. HWP contain C sequestered in woody biomass from the atmosphere through the process of photosynthesis. Atmospheric C can be lowered by increasing C stock in HWP (Dixon and others 1994). The net reduction, however, depends on the final end uses and life of the wood products. Of the total biomass removed from the forests, approximately one-third remains in the forest as logging residue, almost one-fifth ends up as mill residue, and slightly more than half of the total growing stock ends up in final wood products (Table 4).

The harvested wood products including logging residues contain 2.5 million t C. These removals are not considered "loss" if they can be put to uses other than burning. The net carbon storage over a 20-year period (assuming an equal amount of harvest every year, i.e., annual removal of 1.37 million t C from the forest) when put to use as in Figure 3d, would make a total of 50.12 million t C stocked in wood products. Decay and several short-term uses, however, diminishes this stock to 24.94 million t C over the next 20 years. If the forest can sustainably grow this amount and the use pattern remains the same for a defined time period, almost half of the carbon stored in the harvested volume is emitted back to the atmosphere, and the remaining half (i.e., 1.25 million tons annually) of the harvested volume remains stored in harvested wood products.

Table 4.—Annual estimate of volume of wood products.

	Round wood (cft)	Mill residue (cft)	Logging residue (cft)	Total (cft)	Percent
Composite products	11,771,990			11,771,990	3.52
Fuelwood	4,131,773	20,562,169		24,693,942	7.39
Posts, Poles, and Pilings	3,776,820			3,776,820	1.13
Pulpwood	21,734,742			21,734,742	6.5
Sawlogs	117,518,971			117,518,971	35.17
Veneer logs	7,849,775			7,849,775	2.35
Fiber		19,899,719		19,899,719	5.96
Misc. products	468,992	12,511,635		12,980,628	3.88
Unused		8,684,602	105,250,164	113,934,766	34.1
Total	167,253,064	61,658,125	105,250,164	334,161,353	100
Percent	50.05	18.45	31.5		

Data source: USDA Timber Products Output data (1997, 2002, 2007)

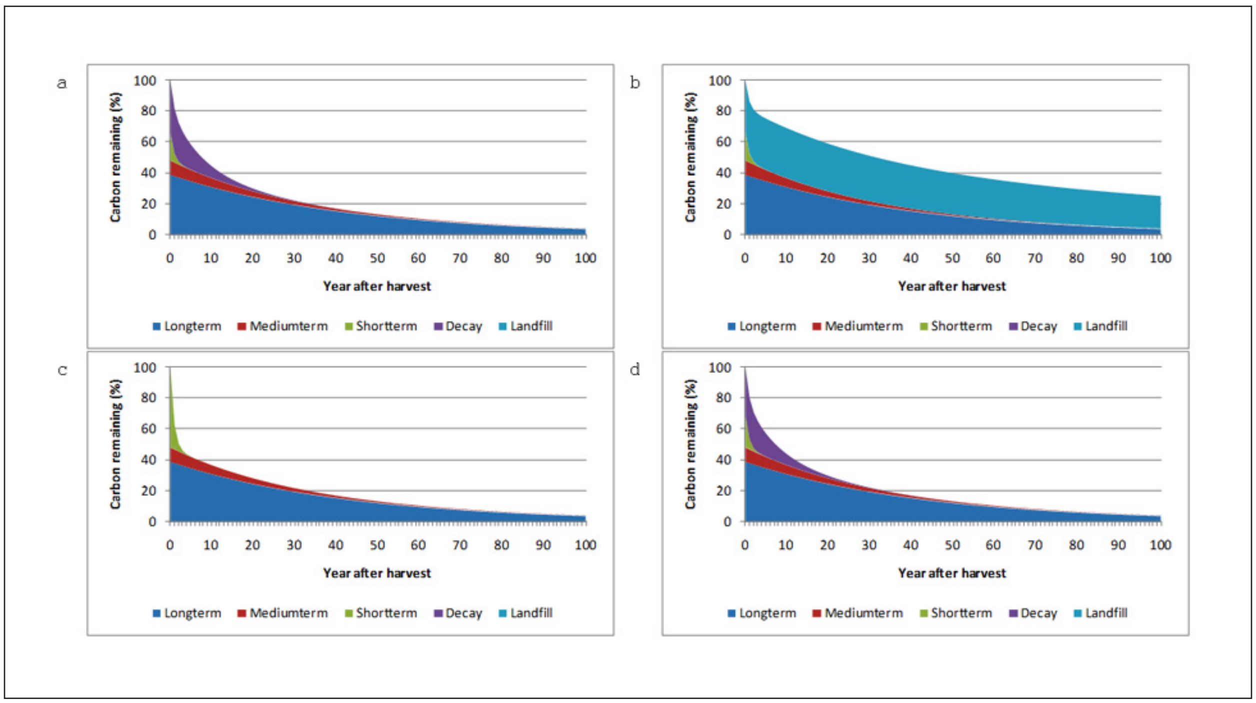

Figure 3.—Effect of different wood product use on carbon storage. (a) Unused residues are left to decay; (b) Unused residues are disposed in landfills; (c) Unused residues are used as biofuel; (d) Unused mill residues are used as biofuel and logging residues are left to decay.

Two million acres of crop lands in West Virginia sequester about 0.05-0.3 t C per acre per year in soil components, resulting in a total C sequestration of 0.1-0.6 (mean 0.35) million tons annually (Sperow and others 2003). In these lands, the growth in the aboveground biomass portion is consumed and/or decomposed within a year and only C in the soil layer lasts for more than a year. More than 452,000 acres of surface mine lands are devoid of biomass cover. As of 2008, about 29 percent of the total active mine lands are being reclaimed and their sequestration is negligible.

CARBON SEQUESTRATION ENHANCEMENT POTENTIAL

Approximately 5.5 million tons of C is annually sequestered in terrestrial components in West Virginia. Forest growth alone provides more than 70 percent of the total annual terrestrial sequestration, followed by sequestration in harvested wood products. Approximately 40 percent of agricultural lands in West Virginia are reported to be marginal land, i.e., agricultural land with severe limitation due to soil, slope, erodibility, and other environmental factors that make the primary agricultural activity less profitable. Afforestation of marginal agricultural lands has the potential for sequestration of 1.37-1.75 t C per acre per year or 1.6-2.06 million t C per year (Niu and Duiker 2006). If this activity is carried out, mean annual C sequestration in agricultural land becomes 1.74 million tons.

The forest C stock can be increased by bringing back the harvested stands to forest use and managing them sustainably. When the growth-to-removal ratio is brought closer to 1 by increasing harvests and re-growing forests in harvested regions, it increases the available growing space and the proportion of young stands. These younger trees sequester more C per unit of time and per unit area, resulting in additional sequestration of 0.94 million t C in the forest ecosystem. Increased harvesting will also contribute 83.4 million cft of wood to the existing estimate of HWP (assuming a constant annual removal rate). With these additional removals, approximately 28.35 million cft of unused wood will be available for potential biomass fuel. The HWP will then sequester an additional 0.29 million t C annually for the entire state.

Reclamation of abandoned mine lands through afforestation would result in an increase in forest area and annual accrual of 0.56 million t C. This estimate uses a C growth rate of 2.3 t C per acre in bare soil, which was obtained from COLE model. Thus, West Virginia could increase the current C sequestration rate by up to 52 percent to achieve a net annual sequestration of 8.40 million tons. These potentials can be achieved by changing land use activities in the marginal agricultural and abandoned mine sites, enhancing forest growth, and increasing the output of sustainable wood products (Table 5).

ALTERNATIVES TO TERRESTRIAL C SEQUESTRATION

Carbon dioxide capture and storage (CCS) is the use of technology to collect and concentrate the CO_2 produced by industrial and energy-related sources, transport it to a suitable storage location, and then store it away from the atmosphere for an extended period of time. Though considered a technologically viable option for reducing atmospheric C significantly, CCS is still an expensive measure. The cost of managing C through CCS ranges from \$60 to \$300 per ton (International Panel on Climate Change 2005, Friedmann and others

Table 5.—Status and potential of terrestrial carbon sequestration in West Virginia.

	Annual Sequestration (million t C)	
Component	Current	Potential
Forest land	3.90	5.00
Agricultural land	0.35	0.14
Harvested wood products	1.25	1.55
Abandoned mine land afforestation	-	0.11
Marginal agricultural land afforestation	-	1.60
Total Sequestration	5.50	8.40
Percent change	100.00	152.72

2006). On the other hand, the cost of carbon sequestration from forest activities ranges from $10 to $150 per ton; the median range lies between $14 and $41/t C (Richards and Stokes 2004). Although cheap, forestry based C sequestration has an upper limit on total sequestration potential. At present, up to 27 percent more C can be sequestered by growing forests trees of suitable species in marginal lands. The avoided C emissions associated with forest-based fossil fuel alternatives, i.e., fuel wood systems, represent a significant amount of C emission savings. Current uses of wood products account for 28,458 tons of C emission annually and supply 455 million British thermal units (BTUs). These wood resources would eventually decay and emit C to the atmosphere but when used as fuel, can help reduce emissions. The energy produced can be considered as savings as this amount of energy would have had to be obtained by burning fossil fuels. BTU savings can be increased further by using unused logging residues to produce energy, which could provide an additional 1.3 billion BTUs and save emissions of 85,000 t C. The economic savings of woody biomass use in power generation can be further increased when we take into account the expense of using geologic sequestration to dispose of the carbon produced during power generation.

DISCUSSION AND CONCLUSIONS

Sustainability is key to West Virginia forests' ability to function continuously as C sinks, which can be achieved by removal without exceeding net growth in a particular year and use of the removed products for long-term purposes or as replacements for fossil fuels. Sustainable harvests have the potential to increase supply by 83.4 million cft of wood, which will contribute to 28.35 million cft of residues for possible biomass-based energy and can prevent approximately 84,451 tons of carbon from being emitted from fossil fuels. Increasing biomass use in power plants can boost demand for timber products, creating an incentive to grow more timber, which will result in more sequestration along with C emission reduction from fossil fuels. Over the long run, the carbon neutrality of biomass use will help achieve the objective of reducing C emissions. When such opportunities exist, the unused woody biomass would start gaining some value, which is likely to motivate land owners to convert surface mine lands and marginal agricultural lands into forestland use. This option is likely to be lucrative if benefits of emerging carbon markets can be made available to land owners who wish to convert the land use to forestry.

Preventing decay of these wood products can help in offsetting C emissions. Short-term wood products, such as pulp and paper, would be considered as lasting for 1 year or less. On the other hand, long-lasting wood products, such as structural timber and furniture, retain stored carbon for an extended period of time and go through multiple instances of recycling. Recycling, avoiding combustion to dispose of wood, and utilizing available residues to replace fossil fuel for power generation would enhance C sequestration. Similarly, proper landfills and wood burials can be helpful in enhancing C sequestration. When available, unused woody residues are used to substitute for some of the coal in power plants, the corresponding amount of C can be saved. Using biomass for energy production combined with CCS at the source will make C emissions negative: C in the atmosphere will be permanently reduced by substituting carbon-neutral, sustainably grown biomass for fossil fuels. The future direction of the current study is towards studying the limits and costs of implementing the strategies identified for C sequestration enhancements in West Virginia.

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