MAXIMIZING CARBON STORAGE IN THE APPALACHIANS: A METHOD FOR CONSIDERING THE RISK OF DISTURBANCE EVENTS

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Abstract.—Accounting for the probability of loss due to disturbance events can influence the prediction of carbon flux over a planning horizon, and can affect the determination of optimal silvicultural regimes to maximize terrestrial carbon storage. A preliminary model that includes forest disturbance-related carbon loss was developed to maximize expected values of carbon stocks. Stand-level optimization was used to develop silvicultural regimes that present a range of forest management benefits, while maximizing expected carbon stocks in the process. Potential benefits include: (1) a reduction in the risk of carbon loss due to disturbance events; (2) increased carbon storage; and (3) the offset of treatment costs through the utilization of treatment-generated woody material. This methodology may also provide a baseline for a full accounting of forestry carbon offset projects. The ability to increase terrestrial carbon density can be limited with the occurrence of disturbance events, as exhibited by some Appalachian forest types. However, silvicultural regimes maximized the expected value of in-forest carbon and carbon in wood products over the life of the analysis period in other Appalachian forest types. The results of this analysis suggest that treatments that effectively manipulate structure, age, and composition have the greatest potential for maximizing terrestrial carbon stocks by simultaneously considering both the risk of emission and storage potential.

INTRODUCTION

Forests are typically a sink for terrestrial carbon (Goodale and others 2002), and forest management has been suggested as a possible means of both reducing carbon dioxide emissions and enhancing carbon sinks (Birdsey and others 2000, Perez-Garcia and others 2005). Increasing the terrestrial density of carbon stored in both forests and wood products could offset up to 20 percent of U.S. emissions by the year 2025 (Chameides and Oppenheimer 2007), and entities such as the Chicago Climate Exchange and the California Climate Action Registry may act as carbon markets for the efficient reduction of atmospheric carbon inputs from forests (Ruddell and others 2007). Forest management objectives include reducing emissions from wildfire and increasing both the proportion and retention of carbon stored in wood products (Birdsey and others 2000).

Under no-management, a forest exhibits the potential for continued growth and subsequent carbon sequestration (Harmon and others 1990, Harmon 2001). The forest will continue accumulating carbon generated through photosynthesis until it is released back to the atmosphere through respiration or the decay of organic matter (Karjalainen and others 1999). Without a disturbance event, this scenario results in a forest that may act as a net carbon sink up to stand ages of 800 years (Luyssaert and others 2008).

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A no-management scenario in disturbance-prone forests of the Appalachian forest region includes the risk of fire, windthrow, ice damage, and pest outbreaks, as well as the carbon emissions associated with such disturbances. Biogenic emissions do not directly follow non-fire-related disturbances, although forests will eventually emit carbon from decay and decomposition. However, pyrogenic carbon emissions are immediate, depend on fire severity (Campbell and others 2007), and can also cause large biogenic emissions in years following the actual fire (Turner and others 2007). Sampson and Clark (1996) suggest that biogenic processes stimulated by tree mortality emit an average of five times the original pyrogenic carbon release over the next 50 years following a fire event. Stand-replacing fire with higher mortality would contribute even greater emissions.

Greenhouse gases, including carbon dioxide, are now considered to be a public health hazard. Mitigating climate change through the reduction of carbon dioxide is a national, as well as global, challenge. Forestry is poised to become a frontrunner in the pursuit of increasing carbon stocks at the terrestrial level. However, to maximize additional carbon storage, methods must be employed to account for uncertainty in terms of carbon losses to the atmosphere. The disturbance-prone forests of the Appalachian region present many opportunities for carbon loss, yet storage can be increased if optimal decision-making processes are employed.

This paper uses simplified examples to present a conceptual method for maximizing the terrestrial carbon storage potential associated with Appalachian forests. The focus is on the proof of concept (i.e., using strategic management regimes to capture potential carbon loss due to disturbance events), not the expected values associated with the example results.

METHODS

Eleven forest types were analyzed for their potential to store aboveground carbon, given the probability of fire and other disturbance events. Forest types were those used to classify the Southern Appalachian Potential Natural Vegetation Groups (PNVG) contained within the LANDFIRE project (Schmidt and others 2002). A summary of the Southern Appalachian PNVG can be found in Table 1.

To demonstrate the development of an optimal forest treatment regime to maximize carbon storage, dynamic programming was applied to solve problems containing two treatment alternatives (control and 15-percent basal area reduction) at each stage for hypothetical stands of each Southern Appalachian PNVG. A simple

Table 1.—Disturbance return intervals and mortality for southern Appalachian forests

Description	PNVG Code	mFRI	Mortality	mDRI	Mortality
Bottomland hardwood forest	R8FPFOpi	108	0.361	90	0.611
Hemlock-white pine-hardwood	R8HEWP	174	0.253	129	0.423
Mixed mesophytic hardwood	R8MMHW	78	0.214	59	0.334
Appalachian dry mesic oak forest	R8OACOm	13	0.177	11	0.237
Eastern dry-xeric oak	R8OAKxe	8	0.178	8	0.238
Appalachian oak hickory pine	R8OHPI	5	0.139	4	0.169
Oak-ash-woodland	R8OKAW	27	0.349	22	0.579
Appalachian shortleaf pine	R8PIECap	6	0.142	5	0.182
Appalachian Virginia pine	R8PIVIap	22	0.302	18	0.502
Southern Appalachian high-elevation forest	R8SAHE	312	0.690	231	0.950
Table mountain/pitch pine	R8TMPP	5	0.150	4	0.200

growth model was applied, where basal area was increased at a constant rate over three 30-year periods, regardless of prior treatment intensity or disturbance event. To simulate the effect of a silvicultural treatment on tree mortality, given the occurrence of fire or other disturbance, standing basal area reduction factors based on LANDFIRE Rapid Assessment Reference Condition Models were used for each PNVG (Schmidt and others 2002). A disturbance event within a treated stand incurred no reduction in the standing basal area, while a disturbance event within an untreated stand incurred mortality set to the corresponding reduction in standing basal area.

To track additional carbon storage over the decision pathway network (Figs. 1 and 2), standing tree basal area was converted to carbon at a conservative rate of 2.85 Mg per m^2 (Matthews 1993, Luyssaert and others 2008). A utilization rate was applied to treatment-generated woody material, and material was allocated to end-use classes with corresponding decay rates. Additional carbon values were calculated as the amount of expected carbon at the end of the regime on a per-Mg of carbon basis. Additional carbon was measured as any carbon storage gained by employing a silvicultural treatment regime over time when compared to the baseline. The baseline carbon value for each PNVG was measured from the decision pathway that underwent no treatment during the 90-year analysis period. Therefore, only decision pathways that included at least one treatment over the analysis period could store additional carbon.

PROBLEM FORMULATION

Decisions during the 90-year analysis period were made every 30 years over three major stages corresponding to growth periods, and two probabilistic stages corresponding to post-disturbance conditions, starting at year 0. At each major stage, two alternatives for each state were possible (no treatment, treatment). The objective function used in the problem formulation maximized the expected value of aboveground carbon stored in standing trees, woody debris, and wood products due to each decision. Major stage computations followed traditional dynamic programming recursive form (Bellman 1957), where maximum carbon storage for stage t is dependent on the maximum carbon storage for stage t + 1.

The element of disturbance within the analysis framework was implemented following the first and third stages. At these stages, the basal area stand descriptor variable was subjected to the decision of no disturbance or disturbance. If there was no disturbance, no disturbance-related mortality was modeled. Mean fire return interval and mean disturbance return interval (mDRI) were used as proxies in the determination of fire risk and total disturbance risk probabilities, respectively. Risk probabilities followed a binomial distribution, where the risk was equal to the probability of a single disturbance event occurrence within a stand over a 30-year period.

The values obtained during the stochastic stages represent the expected amount of terrestrial carbon after accounting for the probability of a disturbance event occurring under specified conditions and assumptions. Fire behavior and disturbance damage were expressed as a mortality rate in the alternative generation procedure. Data and assumptions used to determine the optimal treatment regimes are summarized in Table 2.

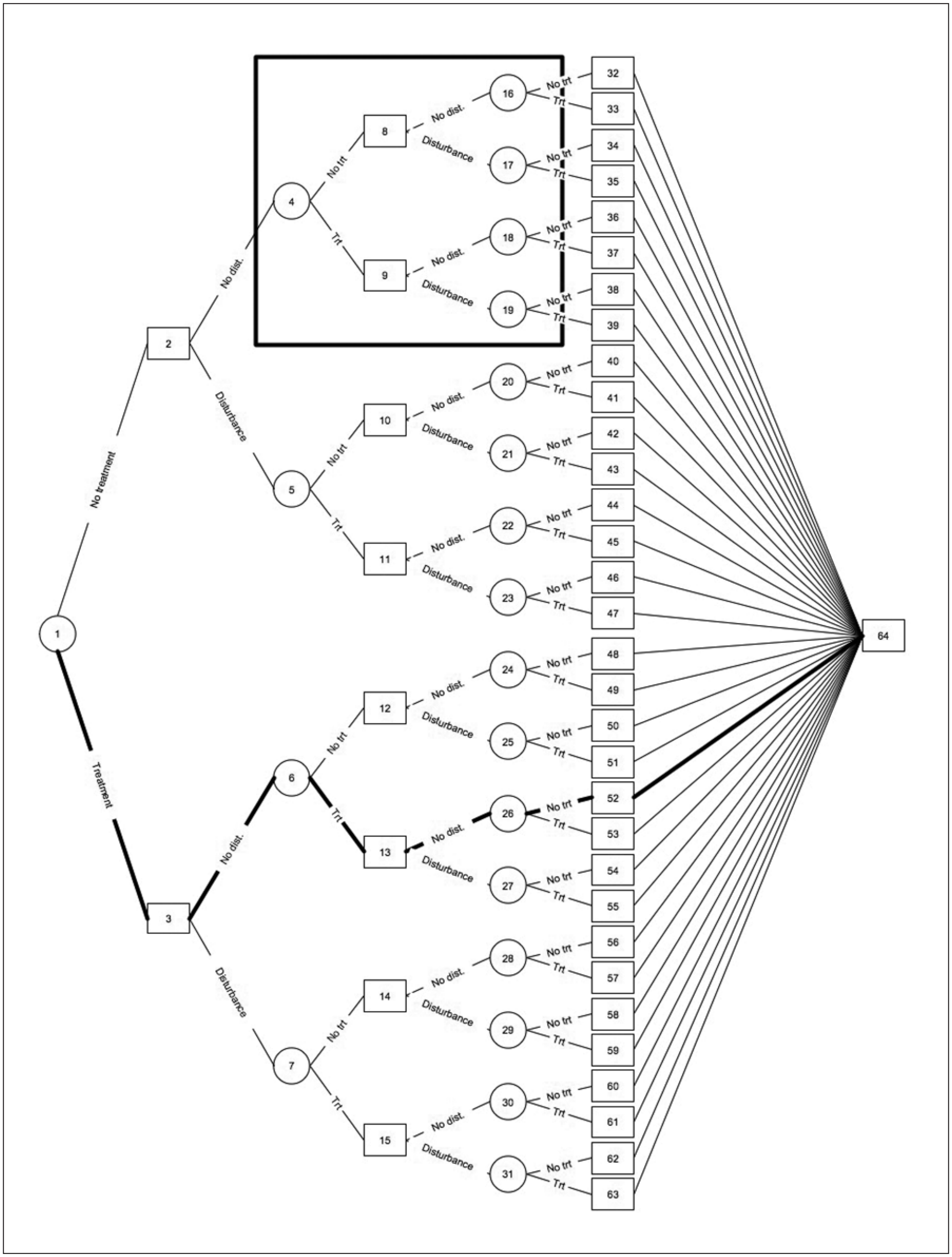

Figure 1.—Example of dynamic programming decision pathway network and optimal regime for PNVG R8OKAW: oak-ash-woodland (boxed area found in Fig. 2).

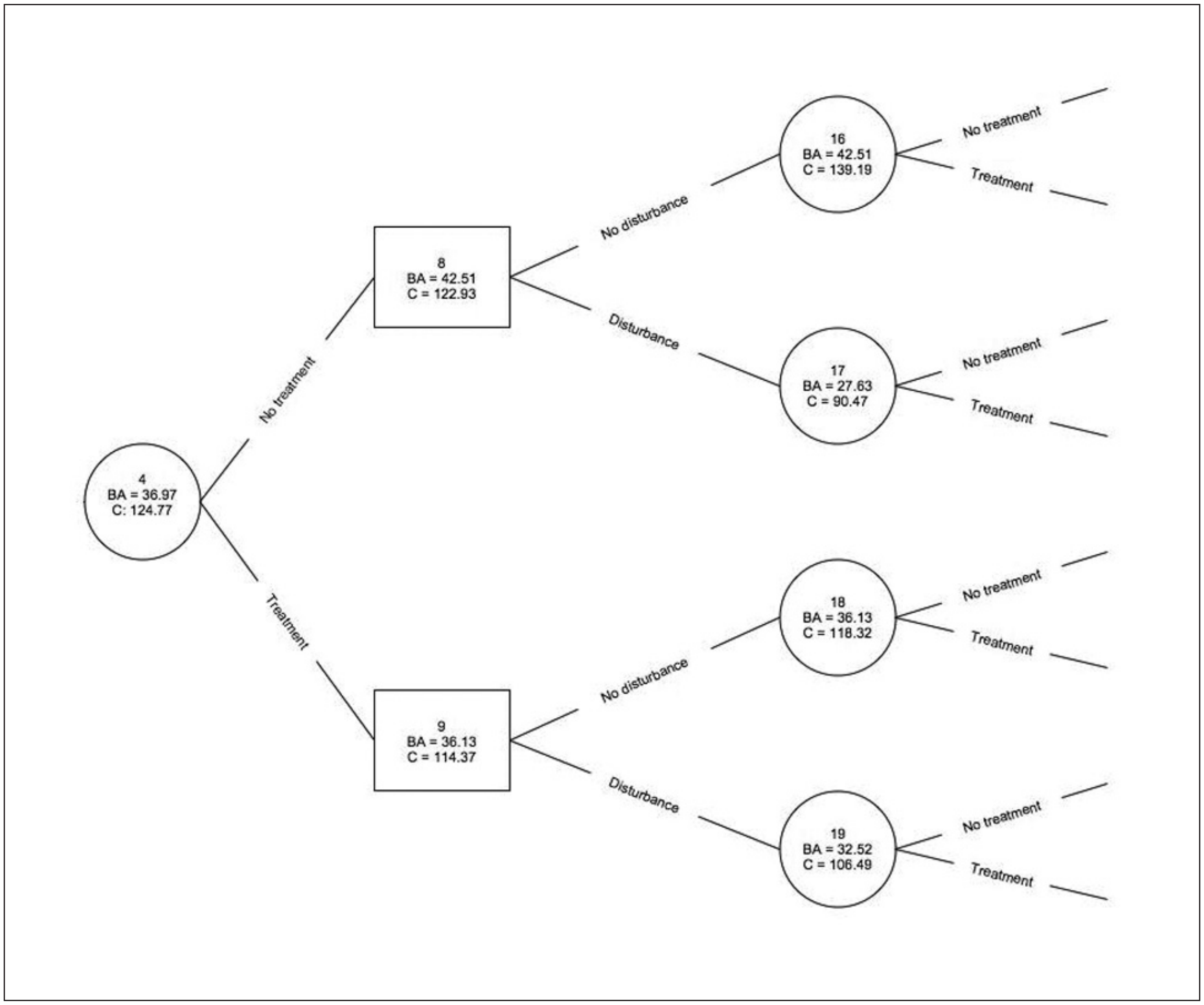

Figure 2.—Detail of decision network incorporating the probability of a disturbance event.

Table 2.-Summary of maximum carbon storage model parameters and assumptions

Parameter Description	Value
30-year ba/ha growth rate (Brooks et al. 2008)	1.25
Fraction of treatment ba/ha removal (Stephens and Moghaddas 2005)	0.15
Initial stand ba/ha (Brooks et al. 2008)	22.06 m^2
Woody material utilization rate (James et al. 2007)	0.85
Utilized woody material annual decay rate (Winjum et al. 1998)	0.01
Non-utilized woody material annual decay rate (Spies et al. 1988)	0.029
Fraction of utilized material subject to decay (James et al. 2007)	0.75
Fraction of utilized material permanently stored (Ximenes et al. 2008)	0.25
ba/ha to carbon volume conversion (Luyssaert et al. 2008, Matthews 1993)	2.85 Mg/m^2

RESULTS

The analysis and optimization procedure yielded silvicultural regimes to maximize carbon storage for each Southern Appalachian PNVG. Incorporating only the risk of fire, we determined that 9 of the 11 forest types showed the maximum carbon storage under the no-treatment scenario (Fig. 2). The two forest types that showed maximum carbon under treatment scenarios were R8OKAW (oak-ash-woodland) and R8PIVIap (Appalachian Virginia pine). Adding the risk of other disturbance to the risk of fire, we determined that an additional three forest types showed the maximum carbon storage under treatment scenarios. The three forest types were R8FPFOpi (bottomland hardwood forest), R8MMHW (mixed mesophytic hardwood), and R8SAHE (Southern Appalachian high-elevation forest).

DISCUSSION

Maximizing terrestrial carbon stocks from forests is a complex problem well suited for the use of dynamic programming for decisionmaking. The results of this analysis suggest that in some cases, treating the forest over time may be beneficial in reducing the risk of carbon emissions due to disturbance events. In turn, accounting for disturbance events can lead toward increased expected values of forest-based carbon stocks over the life of a planning horizon. Figure 3 shows the percent difference in maximum carbon storage over time between the best treatment-decision pathway and the control for each PNVG. A simple way to interpret

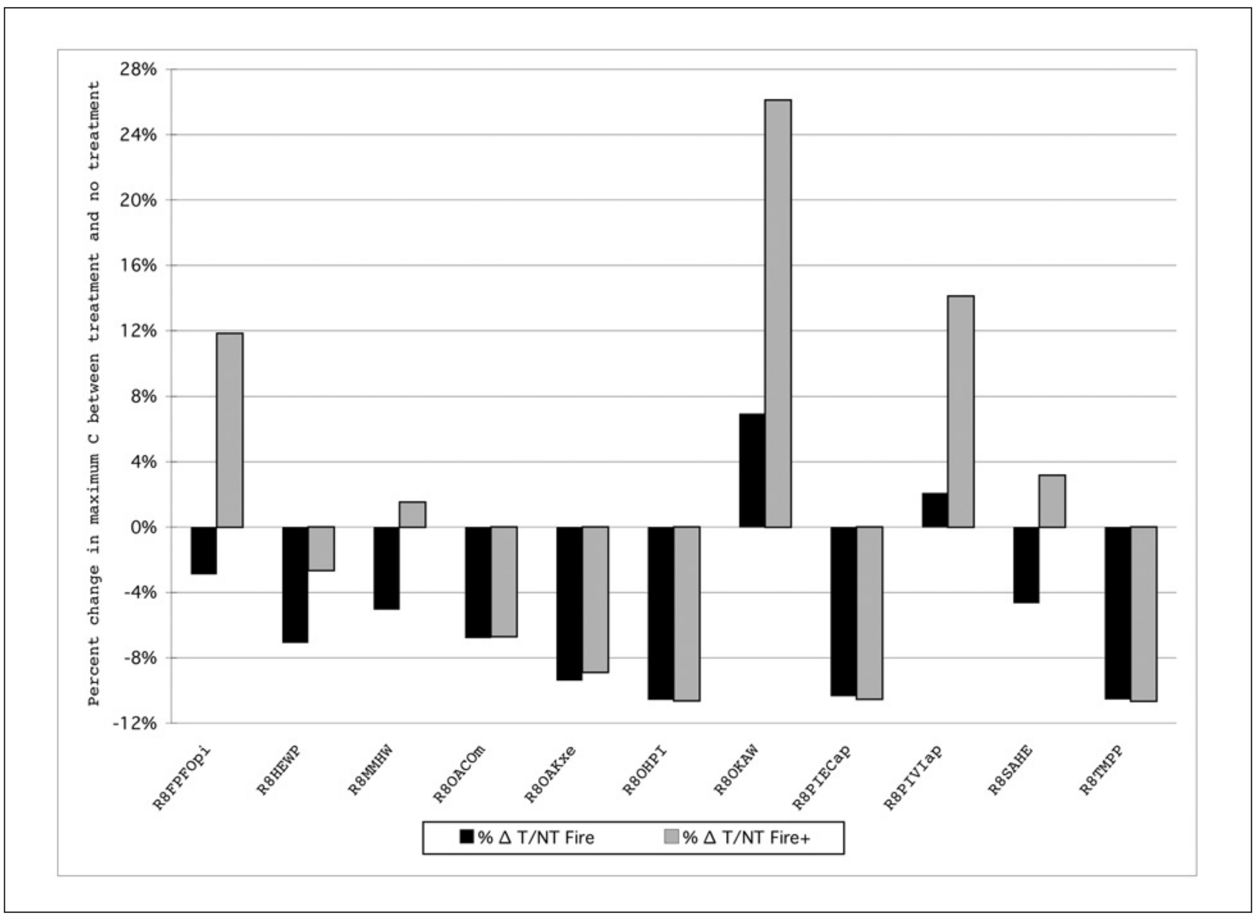

Figure 3.—Percent change in maximum carbon between treatment and control for fire and disturbance return intervals (refer to Results and Discussion for description).

Figure 3 is as follows: If the percent change is positive, expected carbon storage could be maximized by way of a treatment regime within the example provided in this paper; otherwise expected carbon stocks could be maximized without human interference.

Treatment regimes for the fire-risk only analysis maximized 2 of 11 forest types. Treating the oak-ash-woodland showed the potential for increasing carbon stocks by nearly 7 percent over the control, while treating the Appalachian Virginia pine increased stocks by just over 2 percent. Treatment regimes that incorporated the total disturbance risk maximized carbon storage for three more forest types while increasing the expected stocks by an additional 12 to 19 percent for the oak-ash-woodland and Appalachian Virginia pine stands. Of the three additional forest types, the bottomland hardwood forest increased carbon stocks by nearly 12 percent over the control. The Southern Appalachian high-elevation forest and mixed mesophytic hardwood forest types increased stocks by 1.5 to 3.0 percent over the control.

The best method for maximizing terrestrial-based forest carbon stocks depends on the type of forest being analyzed. Appalachian forests with a low mDRI (i.e., less than 20 years) were shown to store more carbon by way of no treatment over the analysis period. A logical explanation could be that the mortality rates associated with frequent disturbances are lower than or close to the treatment intensities. Similarly, Appalachian forests with a higher mDRI (i.e., greater than 20 years) were shown to store more expected carbon by way of a treatment regime, with the exception of R8HEWP (hemlock-white pine-hardwood). This result may be explained by the hemlock-white pine-hardwood forest type exhibiting the second highest mDRI, but also having the second lowest mortality rate of those forests with a mDRI greater than 20 years.

The greatest potential for increasing carbon storage by way of a silvicultural regime exists in bottomland hardwood forests, oak-ash-woodlands, and Appalachian Virginia pine stands. Oak-ash-woodlands have the most potential, showing an increase of more than 26 percent over the control. When the no-management regimes stored more carbon compared to treated stands, there was no difference greater than 11 percent.

There is also the opportunity to use increased carbon storage from forests as an investment or cost-offsetting measure. Assuming a value of $5.83 per Mg carbon (Hamilton and others 2008), monetary returns ranging from approximately $4 to upwards of $57 per hectare may be possible, depending on initial forest and market conditions. Furthermore, if a silvicultural regime is expected to maximize forest-based carbon stocks, then there is also potential for revenue from the sale of treatment-based woody material if the markets exist.

Overall, terrestrial carbon stocks potentially can be increased by strategically managing the disturbance-prone Appalachian forests. As shown in this analysis, not all forest types stand to benefit from silvicultural treatment regimes in terms of carbon storage over time. However, some forest types may benefit. These forest types are prime candidates for further theoretical and empirical research to determine their potential for contribution to the low-carbon economy. Furthermore, added complexity, such as increasing the number of decision stages, expanding the silvicultural treatment options, and modeling the response of forest stands to both disturbance events and treatments, can lead towards increased carbon storage in other forest types.

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