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Modeled effects of soil acidification on long-term ecological and economic outcomes for managed forests in the Adirondack region (USA)

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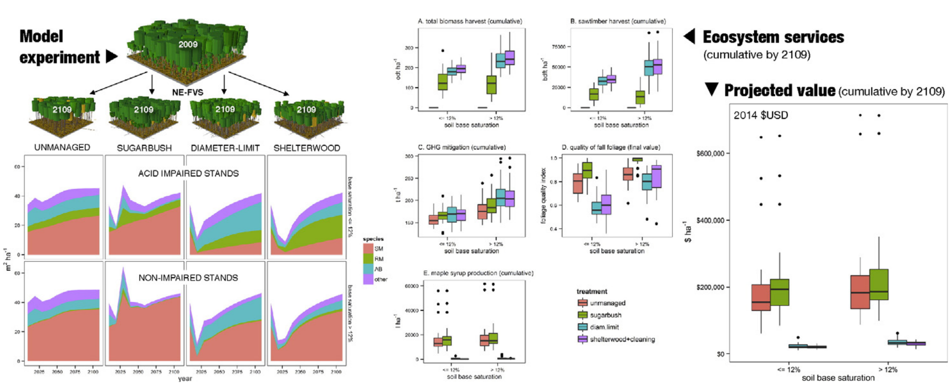
HIGHLIGHTS

- We modeled forest management outcomes in acidified forests of the Adirondacks (US).
- Management of acidified forests results in loss of sugar maple as dominant species.
- Estimated economic value decreased by ~$214,000 ha^{-1} on acidified soils.
- Healthy forests can be managed to sustain sugar maple and long-term economic values.
- Legacy of acid rain may constrain options for sustainable forestry and its benefits.

GRAPHICAL ABSTRACT



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ABSTRACT

Sugar maple (*Acer saccharum*) is among the most ecologically and economically important tree species in North America, and its growth and regeneration is often the focus of silvicultural practices in northern hardwood forests. A key stressor for sugar maple (SM) is acid rain, which depletes base cations from poorly-buffered forest soils and has been associated with much lower SM vigor, growth, and recruitment. However, the potential interactions between forest management and soil acidification – and their implications for the sustainability of SM and its economic and cultural benefits – have not been investigated. In this study, we simulated the development of 50 extant SM stands in the western Adirondack region of NY (USA) for 100 years under different soil chemical conditions and silvicultural prescriptions. We found that interactions between management prescription and soil base saturation will strongly shape the ability to maintain SM in managed forests. Below 12% base saturation, SM did not regenerate sufficiently after harvest and was replaced mainly by red maple (*Acer rubrum*) and American beech (*Fagus grandifolia*). Loss of SM on acid-impaired sites was predicted regardless of whether the shelterwood or diameter-limit prescriptions were used. On soils with sufficient base saturation, models predicted that SM will regenerate after harvest and be sustained for future rotations. We then estimated how these different post-harvest outcomes, mediated by acid impairment of forest soils, would affect the potential monetary value of ecosystem services provided by SM forests. Model simulations indicated that a management strategy focused on syrup production – although not feasible across the vast areas where acid impairment has occurred – may generate the greatest economic return. Although pollution from acid rain is declining, its long-term legacy

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in forest soils will shape future options for sustainable forestry and ecosystem stewardship in the northern hardwood forests of North America.

1. Introduction

Acidic deposition has declined dramatically in North America over the last two decades (U.S. Environmental Protection Agency, 2013), but its long-term impacts on forest ecosystems are still largely unresolved (Long et al., 2011). Where deposition inputs exceed soil buffering capacity, acid pollution causes depletion of nutrient pools and changes in soil chemistry that increase biological exposure to toxic metals such as inorganic aluminum (Driscoll et al., 2001; Lawrence et al., 1995). Recovery of base cation pools in acidified forest soils underlain by base-poor parent materials will likely be slow (Lawrence et al., 2015; Johnson et al., 2008), such that the legacy effects of ecosystem acidification will continue to shape forest composition, productivity and health, even as deposition approaches pre-industrial levels (Long et al., 2011). Given that extant forests may not be in equilibrium with the current state of soils, climate or other ecosystem state factors, such legacy impacts of ecosystem acidification on forest trees have been difficult to discern (Moore et al., 2015; Lovett et al., 2009).

Sugar maple (*Acer saccharum* Marshall) is among the most abundant and ecologically important trees in the northern hardwood forests of North America (USDA Forest Service, 2013; Wilson et al., 2012). Sugar maple (SM) also represents one of the most valuable renewable resources in eastern North America, as it supports a multi-billion dollar syrup industry, and provides high-value wood products, as well as cultural benefits including attractive fall foliage. Managing for the shade-tolerant, relatively slow-growing SM is often a primary objective of silviculture in the region (Germain et al., 2015; Nolet et al., 2014; Schwartz et al., 2005). Forest management practices such as the selection system seek to promote SM in managed forests where competitive interference and selective browsing can inhibit regeneration (Nyland, 2007).

Unfortunately, SM is threatened across much of its range by the cumulative impacts of acid deposition (Sullivan et al., 2013; Long et al., 2009; Duchesne et al., 2002), which reduces the availability of key nutrients such as calcium (Ca) and mobilizes toxic metals such as aluminum (Al) in poorly buffered forest soils (Lovett et al., 2009; Driscoll et al., 2001; Lawrence et al., 1995). Prior research has established that SM has a high demand for calcium (Long et al., 2009; Hallet et al., 2006; Lovett et al., 2004; Horsley et al., 2000; van Breemen et al., 1997) and that its relative abundance in northern hardwood forests increases with soil pH and Ca availability (Beier et al., 2012). Although SM may suffer from nutrient limitation on naturally base-poor soils (Long et al., 2011), chronic acidification has driven soil chemistry beyond the natural range of variation of the hardwood forests where SM is found (Johnson et al., 2008), creating a severe and chronic stressor for extant SM populations across much of northeastern North America (Duchesne et al., 2002; Long et al., 2009), where deposition inputs typically exceed critical loads (McNulty et al., 2007). Several experiments have demonstrated recovery of growth and crown vigor in SM stands following the application of lime ($CaCO_3$) to improve Ca availability (Battles et al., 2014; Moore and Ouimet, 2006; Long et al., 1997).

In the forests of the Adirondack region of New York State (USA), a ‘hot-spot’ of acid pollution in eastern North America (Kahl et al., 2004; Driscoll et al., 2001), a recent study by Sullivan et al. (2013) found that SM had lower vigor and average growth rates on poorly-buffered, chronically acidified soils. Most notably, the study demonstrated that SM recruitment was poor or absent on acid-impaired soils, even though SM was the dominant canopy species in all cases. Very few or zero seedlings were present on sites with <12% soil base saturation, a level associated with very low exchangeable soil Ca^{2+} (<2.5 cmolc kg^{-1} in the A horizon) and the mobilization of inorganic Al^{3+}, which is toxic and inhibits Ca uptake by plant roots (Cronan and Grigal, 1995).

Based on the field observations of Sullivan et al. (2013) and other studies noted above, we hypothesized that inhibition of SM recruitment on culturally acidified soils could pose obstacles for well-established silvicultural practices intended to regenerate SM as the dominant canopy species. In other words, we posited that SM stands on culturally acidified soils would lack sufficient regeneration to establish a new SM cohort if the existing overstory were to be removed, either by harvest or another large-scale disturbance (such as an ice storm). Removal of the SM canopy in acid-impaired forests would then result in a transition to red maple (*Acer rubrum* L.) and American beech (*Fagus grandifolia* Ehrh.), which are already abundant in the advance regeneration of acidified Adirondack hardwood forests (Sullivan et al., 2013) and are more tolerant of acidic, nutrient-poor soils than SM (Long et al., 2009; Lovett and Mitchell, 2004). As a result, SM may not recover to its previous dominance in the stand, even if forest management practices intended to promote SM regeneration are used.

To test this hypothesis, we conducted a model experiment to determine how interactions between forest management and the acid-impairment of soils may shape long-term outcomes in northern hardwood forests. Model simulations were initialized with extensive field data from hardwood stands in the Adirondacks with SM common in the overstory. Study sites collectively represented a regional gradient in acid impairment of soils due to chronic acidic deposition (Sullivan et al., 2013). Stands were simulated for 100 years under several silvicultural prescriptions, including a shelterwood harvest, a sugarbush, and an unharvested reference. We also included a diameter-limit harvest, which, although common in the region, is generally not considered a recommended silvicultural prescription (Nyland, 2007).

Regeneration failure of SM in acid-impaired forests will likely have significant economic and cultural implications. Sugar maple provides valuable ecosystem services (ES) to society at local, regional and global scales, including wood products, maple syrup, carbon storage, and aesthetic enjoyment of colorful fall foliage. Other supporting services associated with SM, such as more rapid nitrogen cycling in SM-dominated forests (Lovett and Mitchell, 2004), could help to mitigate nitrogen deposition impacts on surface water quality (Beier et al., 2015). Forests dominated by SM also foster greater biodiversity of herbaceous plants and soil fauna (Beier et al., 2012), suggesting a possible keystone role for this species in northern forest ecosystems.

If the future composition of hardwood stands transitions away from SM, we can expect the forest's capacity to provide benefits associated with SM to also change. To estimate this change, we translated outputs of our forest model experiment (silviculture × soil chemistry) into measures of ES (potential benefits) and estimated their monetary value (2014 $USD), with a focus on five potential benefits: production of biomass, production of sawtimber, production of maple syrup, carbon storage and fall foliage. We hypothesized that changes in potential benefits would reflect an overall net decrease in the economic value of forests where SM fails to regenerate and is replaced by other less valuable species. However, these benefits are not wholly unique to SM, and with the exception of syrup production, they are also provided by other co-occurring tree species. Therefore, we assessed ES based on the entire stand-level tree inventory outputs from the model simulations. This allowed us to give ‘credit’ to the other tree species for the potential benefits that they provide, such as carbon mitigation and production of wood products, which could be largely unaffected by SM loss at the stand level.

This study is part of a broader effort to quantify the ecosystem outcomes and legacy effects of acid pollution using endpoints that are directly relevant to human well-being and useful for decision-making. Our application of the ES framework follows prior efforts to combine ecological and social data to assess the system's capacity to provide services, i.e., the 'potential benefits' that may flow to society (Caputo et al., 2016; Beier et al., 2015). Here, we translate these measures of potential benefit to monetary units (2014 $USD) on a per unit area basis, which reflects a partial and theoretical estimate of potential net present value. Our analysis does not capture actual flows of benefits to people or attempt to quantify actual net revenues or option values in our specific study area. Instead, we sought to elucidate how acid rain has shaped the contemporary economic values as well as future options for sustainable forest management and ecosystem stewardship in the northern hardwood forests of North America.

2. Methods

2.1. Vegetation and soils data

Data used in forest model simulations were drawn directly from Sullivan et al. (2013) and Bishop et al. (2015). In 2009, we established 50 forest inventory plots located within and distributed among 20 first-order stream catchments (two or three plots per catchment) in the western Adirondack Mountains. Study catchments collectively encompass the range of soil pH and base cation saturation found in the Adirondacks, from poorly buffered and culturally acidified soils to well-buffered and calcium-rich soils (Sullivan et al., 2013; Beier et al., 2012). Each plot was 50 × 20 m (0.1 ha) in size and included SM as a dominant or co-dominant canopy species. Within each plot we sampled one complete profile down to the C horizon, and collected a 10 × 10 cm block of forest floor (Oe and Oa/A horizon) at five locations along a transect through the center of the 50 m plot length. Soil samples were analyzed for exchangeable cations and pH (0.01 M $CaCl_2$) as described in Sullivan et al. (2013). Base saturation was calculated as the sum of base cations (Ca, Mg, K, Na) divided by total cations (Ca, Mg, K, Na, H, and Al). In each plot we measured tree diameters at breast height (DBH), and determined sapling and seedling counts in nested quadrats. Increment cores (two radii per tree) were collected from mature (≥30 cm DBH) dominant or co-dominant SM trees (Bishop et al., 2015; Sullivan et al., 2013).

2.2. Model simulations

We used the Northeast variant of the Forest Vegetation Simulator (NE-FVS, Dixon and Keyser, 2008) to simulate stand development. NE-FVS is a distance-independent forest growth and yield simulation model developed by the U.S. Forest Service. To parameterize the model, we scaled the tree and sapling inventories from each of the 50 plots to a single 0.4 ha stand. For each canopy tree for which growth rates were measured using tree cores (see Bishop et al., 2015), mean annual growth increment during the 20th century was also input to the model. These empirical measures of growth were used to calibrate simulated growth rates within a given stand.

NE-FVS does not currently model full establishment of regeneration. The model's partial establishment sub-model requires the user to manually input the species, density, and timing of regeneration events. We used the seedling inventory (i.e. quadrat data) from each of the 50 sample plots to represent a single regeneration event in the initial time step of the model. No additional regeneration events were simulated during subsequent time steps.

Each plot was then subjected to each of four different management treatments (a total of 200 plot × treatment combinations) and growth was simulated over a 100-year period (2009–2109) using 10-year time steps. We simulated four treatments: an unmanaged reference, a diameter-limit harvest, a shelterwood harvest, and a prescription intended to optimize production of maple syrup, i.e., a "sugarbush" treatment. The diameter-limit treatment consisted of a 12.7 cm diameter limit harvest in 2010. The shelterwood treatment was based on the two-phase shelterwood system (Nyland, 2007). Stands were initially thinned from below in 2010 to a residual basal area of 9.2 m^2 ha^{-1}. During the first cut, no trees <5.1 cm DBH were cut. In 2020, the final removal cut took out all remaining trees >12.7 cm. In conjunction with the removal cut, a cleaning treatment was also simulated in 2020 to control vegetation that might interfere with sugar maple regeneration. Simulating chemical girdling, the treatment killed stems of American beech and striped maple (*Acer pensylvanicum* L.) from 0 to 12.7 cm; 80% of stems in this size class were killed and mortality was assumed to be distributed evenly across the range. The sugarbush treatment consisted of two steps; first all stems of species other than sugar maple were removed in a heavy cleaning operation in 2010. Thereafter, whenever they attained a relative density of 80% or more, based on using Curtis's relative density index (Curtis, 1982), stands were thinned to a relative density of 50% with the caveat that harvesting could occur in a given stand no more frequently than once in 20 years. A target density of 50% was chosen to correspond to a slightly more intense thinning than a standard B-level thinning (Nyland, 2007), based on Morrow's (1976) recommendations for converting an untended maple stand into a working sugarbush.

2.3. Ecosystem services assessment

The NE-FVS outputs include a full vegetation inventory for each of the 200 stand × treatment permutations at each of the 11 time steps, and an inventory of harvested stems in the three treatments that included harvesting. Based on these data, we estimated five potential ecosystem benefits: provision of wood products that include [of] total biomass for energy and sawtimber for building, provision of maple syrup, greenhouse gas (GHG) mitigation, and the aesthetic values associated with fall foliage.

Biomass provision represents the total resource that may be produced through management and is made available for the production of wood products, use as an energy feedstock, etc. It was calculated by converting diameters of harvested stems to estimates of standing biomass using Jenkins et al.'s (2003) allometric equation for mixed hardwoods. Estimates of the provision of sawtimber volume were taken directly from the model outputs. NE-FVS reports volume in terms of estimated board-feet (bdft), a standardized unit used by industry and government across North America. There is no universal conversion between board-foot volume and simple cubic volume. Therefore, in this study, we used the conversion factor 423.78 bdft m^{-3} to translate board-foot volume to cubic volume.

To quantify the potential benefit of greenhouse gas mitigation, we adopted the framework of Lippke et al. (2012) in which forests are assumed to provide carbon benefits through three main channels: the sequestration and storage of carbon in the forest ecosystem, the storage of carbon in long-lived wood products (LLWD), and the provision of woody biomass used in place of fossil fuels and carbon-intensive building products such as steel and concrete (the product substitution benefit). We estimated the aboveground carbon storage in standing biomass using the aforementioned allometric equation from Jenkins et al. (2003) multiplied by a carbon:biomass ratio of 0.498:1 (Birdsey, 1992). In scenarios in which harvesting took place, we assumed that all harvested biomass suitable for sawtimber would be used in the production of long-lived wood products (LLWP). To estimate carbon stored in LLWD, we assumed that carbon in biomass harvested and utilized for LLWP formed a carbon pool with an 80-year half-life (Perez-Garcia et al., 2005). We translated commercial sawtimber volumes to cubic volume using the aforementioned conversion factor and then converted volume to mass using an estimated wood density of 640 kg m^{-3}. Additionally, we assumed that the substitution of LLWD for more carbon-intensive building materials provided a benefit of 2.1 tons of carbon for every ton of carbon in the LLWD (Lippke et al., 2012). We assumed that all harvested biomass that was unsuitable for sawtimber would be used in the form of cordwood as a source of thermal energy in place of natural gas. We further assumed that 30% of harvested cordwood remained on site as residues (Lippke et al., 2011). In order to calculate the product substitution value of biofuels, we assigned a value of 0.49 units of carbon displaced for every unit of carbon in the biomass itself, based on Lippke et al. (2012). Finally, we assigned a carbon penalty equivalent to 6% of the pre-harvest stand carbon to each of the managed stands to account for greenhouse gas emissions associated with the harvesting and processing of biomass (Lippke et al., 2011). Belowground carbon storage was not included in the analysis.

Potential maple syrup production was estimated from the standing tree inventory using the sustainable tapping guidelines of Heiligmann et al. (2006), in which all sugar maple trees over 25.4 cm are given a single tap and all maple trees over 45.7 cm are given two taps. The number of taps in each stand was then multiplied by the average annual yield per tap in New York State, 0.862 L, to estimate the total potential annual syrup yield per hectare. We estimate annual yield as the average of reported yields in 2012, 2013, and 2014 (USDA NASS, 2014).

Although anecdotal information suggests that sugar maple is more highly valued for its fall foliage than many other co-occurring trees in northern hardwood forests, we were unable to locate any studies that substantiated this social preference. Therefore, we calculated the potential benefit of fall foliage based on a range of theoretical weights (0–1) for preference of sugar maple as well as preference for all other deciduous trees combined. The metric was calculated as the proportion of stand basal area represented by sugar maple multiplied by the appropriate preference weight, plus the proportion of basal area represented by other hardwoods multiplied by a second preference weight. We assumed that non-deciduous conifers provided no benefit for fall foliage viewing. Possible values of the metric ranged from 0 in the situation where no foliage is valued (both preference weights are zero) or where no deciduous trees exist in the canopy to 1, where the entire stand consists of deciduous trees and both preference weights equal 1. As our base case, we adopted preference weights of 1 and 0.5 for sugar maple and other hardwoods, respectively. In other words, we assumed sugar maple fall foliage was twice as preferable as that of other deciduous trees.

2.4. Monetary valuation

To estimate the economic values associated with ES, we used a benefit transfer approach (Table 1). If suitable for sawtimber, harvested stems were valued using mean stumpage values for the Adirondack region as compiled by the New York State Department of Environmental Conservation (2014). Otherwise, stems were valued using mean stumpage values for cordwood. Like the board-foot, there is no universal conversion factor between a cord and SI units of volume or mass. In order to calculate the value of harvested cordwood, we used the conversion factor 1181 kg cord^{-1} to convert biomass to volume. For the purposes of valuation, it was assumed that 30% of harvested cordwood was left onsite as residues (Lippke et al., 2011). The value of greenhouse gas mitigation was taken from an estimate of the mean global price of carbon as reported by the World Bank (2014). The value of maple syrup production was estimated by averaging the unit value of maple syrup in 2011, 2012 and 2013 (USDA NASS, 2014). We were unable to find a specific estimate of the economic value of fall foliage viewing, so we derived a proxy value from Loomis's (2005) estimates of monetary values for U.S. recreational activities. Specifically, we used the average of Loomis's (2005) values for sightseeing, pleasure driving, and 'general recreation' for the northeastern USA. These values were reported in terms of \$ trip^{-1} — as opposed to values per unit area. In order to reconcile these values with our estimated values of the other ES, which were measured in terms of \$ ha^{-1} year^{-1}, we assumed that each of the simulated stands provided an average of one recreational trip per hectare per year. All values were translated to 2014 dollars using the U.S. Department of Labor Bureau of Labor Statistics inflation calculator (U.S. Department of Labor, 2015). The same service values were used for each time step in the simulation and no discount rate was applied.

Table 1
Monetary values of ecosystem services in the western Adirondack region of New York State, USA.

Ecosystem service	Value	Source
Sawtimber (by species)	\$55–\$400 mbft^{-1}	NY DEC (2014) (2014 dollars)
Cordwood (by species)	\$5–\$10 cord^{-1}	NY DEC (2014) (2014 dollars)
GHG mitigation	\$4.9 CO_2-eq^{-1}	World Bank (2014) (2013 dollars)
Maple syrup	\$11.38 L^{-1}	USDA NASS (2014) (2011–2013 dollars)[a]
Fall foliage viewing	\$53.22 trip^{-1}	Loomis (2005) (2004 dollars)[b]

[a] Average prices for 2011–2013 for New York State.
[b] Average of the per-trip values of sightseeing, pleasure driving, and "general recreation" for the northeastern USA.

2.5. Analysis

We used a model selection approach to examine the relationship between soil acidity, silviculture and the end-of-simulation (2109) values of seven output variables: SM basal area, five measures of potential benefits, and total estimated monetary value. Each stand was simulated under each of the four silvicultural treatments, but was assigned to one of two possible soil acidity categories based on soil chemistry measurements at the stand level. Stands were either in the group with ≤12% base saturation ($n = 26$) or the group with >12% base saturation in the upper B horizon ($n = 24$). The base saturation threshold of 12% reflects the point at which inorganic Al becomes mobilized in acid-impaired forest soils — a condition that inhibits Ca uptake by plants and is known to be associated with poor health and vigor as well as lower growth rates in extant SM populations (Sullivan et al., 2013; Long et al., 2009). The condition in hardwood forest soils is attributable to impacts of chronic acidic deposition (Sullivan et al., 2013).

For each of the seven output variables, we constructed four models using two predictor variables, soil base saturation (<12% or >12%) and silviculture (unmanaged, sugarbush, diameter limit, shelterwood). Models were based on both predictor variables individually, both variables combined, and both variables combined plus an interaction term. We built linear mixed models in R 3.0.2 (R Core Team, 2013) using the package 'lme4' 1.1–6 (Bates et al., 2014). We used Akaike's Information Criterion corrected for small sample sizes (AICc) to compare and select among models using the package 'AICcmodavg' 2.0-1 (Mazerolle, 2014). As a measure of goodness-of-fit, we calculated the conditional R^2 (R^2_c) for top-ranked models using the package 'MuMIn' 1.12.1 (Barton, 2014). For each term included in the top-ranked model, we estimated 95% confidence intervals around the differences between level means, and intervals that did not include zero were interpreted as significantly different means. Because of the large number of variables in this analysis and the sensitivity of results to their definition, we created an interactive visualization that allows the user to adjust service values, foliage preference weights, trip frequency, and other parameters important to the analysis. With these inputs, the results can be recalculated based on any time step in the simulated time series. The visualization is available at http://www.forestecoservices.net/smpcomp.php.

3. Results and discussion

3.1. Regenerating sugar maple in managed stands

Based on NE-FVS simulations of 50 northern hardwood stands, projected basal area of sugar maple in 2109 ranged between 1.1 and 51.6 m^2 ha^{-1} (Fig. 1). The top-ranked model of SM basal area (Akaike weight = 1.000, R^2_c = 0.881) included both soil acidity and silviculture, as well as an interaction term (Table 2). For each of the four simulated silvicultural prescriptions, stands on moderate to well-buffered soils (base saturation > 12%) contained greater SM basal area than acid-impaired soils (base saturation < 12%) after 100 years of simulated growth. This was due to a confluence of several factors, including greater initial SM basal area on well-buffered sites, more SM seedlings to provide ingrowth, and a positive correlation between diameter growth of mature SM trees and soil base saturation (Bishop et al., 2015; Sullivan et al., 2013).

On both acid-impaired and well-buffered soils, the sugarbush prescription increased SM basal area relative to the unmanaged reference stand. We expected this result given that treatment involved removing stems of all other species as well as a series of intensive thinnings intended to reallocate growing space to the largest (and presumably most vigorous) SM trees.

Diameter limit harvest resulted in the lowest future SM basal area on both acid-sensitive and well-buffered sites. The effect was most pronounced on the acid-sensitive sites, where a lack of adequate SM regeneration resulted in a compositional shift towards American beech and red maple. On the well-buffered sites, there was ample SM regeneration, but many seedlings were suppressed by competing saplings and sprouts. Previous research has documented the tendency for SM dominance to decline after even-aged management when competing vegetation – especially beech – is not controlled (Wagner et al., 2010; Nyland, 2007; Wang and Nyland, 1993).

In contrast, the shelterwood prescription included a cleaning procedure intended to remove vegetation (such as beech sprouts) that could interfere with SM regeneration. On the acid-impaired sites, this procedure had little or no effect because of the absence of SM seedlings and saplings. We therefore found no significant difference between the shelterwood and diameter limit prescriptions in terms of projected SM basal area 100 years after harvest (CI = [−0.8, 7.0]). On the well-buffered sites, however, the cleaning procedure was effective in releasing SM regeneration from interference, and SM was successfully established in the new cohort. We found no significant difference in projected SM basal area between the shelterwood and reference stands at the end of the 100-year simulation (CI = [−5.3, 2.8]). This finding supports current recommendations regarding the use of herbicides to control beech when undertaking regeneration harvests in mixed northern hardwoods stands (Nyland, 2007).

The rate of regrowth predicted by NE-FVS for harvested stands was similar in magnitude to that measured at the Turkey Lakes Watershed (TLW), a long-term experiment in Ontario, Canada investigating the effects of common silvicultural practices on ecosystem dynamics in northern hardwoods forests (Kreutzweiser et al., 2004). In our simulations as well as in the TLW experiments, stands recovered 27–30% of pre-harvest basal area within 10 years of diameter-limit harvest

Table 2
Top-ranked statistical models predicting future stand composition and potential ecosystem service provision from sugar maple (*Acer saccharum*) forests in the Adirondacks (USA). Listed models are the most highly ranked from the complete set of models predicting seven response variables in terms of silvicultural treatment, the acidity of organic soil horizons (base saturation ≤ 12% "acid-sensitive" or > 12% "well-buffered"), and the interaction between the silviculture and acidity variables. Akaike weights are listed for each model as measures of the relative likelihood of that model compared to the other candidate models in that set. All models with Akaike weights > 0.25 are listed. Conditional R^2 (R^2_c) is reported as a measure of the model goodness-of-fit. Response variables were derived from model outputs and represent the cumulative or final state (in the case of basal area and foliage quality index) of the variable at the end of the period 2009–2109. Model parameterization is based on forest inventory and growth data from 50 stands in the western Adirondack region of New York State, USA.

Top model(s)	Akaike weight	R^2_c
Sugar maple basal area = treatment + acid + (treatment ∗ acid)	1.000	0.881
Total biomass yield = treatment + acid + (treatment ∗ acid)	1.000	0.895
Total sawtimber yield = treatment + acid + (treatment ∗ acid)	1.000	0.873
Greenhouse gas regulation = treatment + acid + (treatment ∗ acid)	1.000	0.932
Fall foliage quality = treatment + acid + (treatment ∗ acid)	1.000	0.814
Maple syrup = treatment	0.702	0.675
Maple syrup = treatment + acid	0.283	0.675
Total cumulative service value ($) = treatment	0.666	0.657
Total cumulative service value ($) = treatment + acid	0.320	0.657

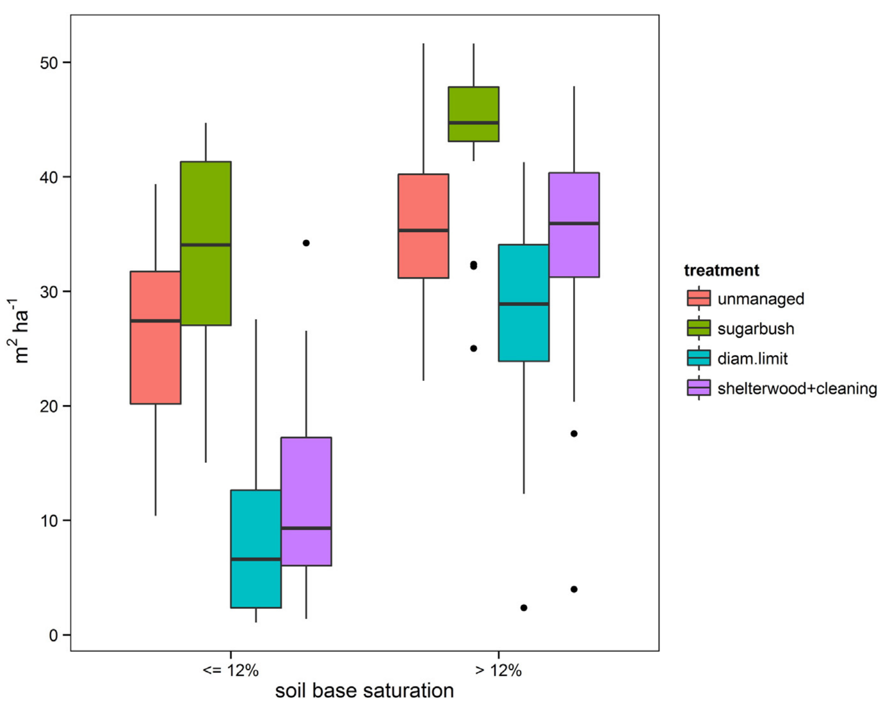

Fig. 1. Projected basal area of sugar maple (*Acer saccharum*) in 2109, under different silvicultural treatments and soil base saturation conditions, in 50 stands in the western Adirondack region of New York State, USA. Of the 50 stands, 26 plots were acidified (≤12% soil base saturation in the upper B horizon) and 24 were well-buffered (>12% soil base saturation). Each stand was simulated under each of four silvicultural treatments using NE-FVS. Boxplots are defined by the median, first and third quartiles. Plot whiskers designate the minimum and maximum values within 1.5 times the interquartile range; all points whose values fall outside this range are plotted as outliers.

(unpublished data from Frederick D. Beall). In the same time frame, SM basal area at TLW recovered to 21% of its pre-harvest levels as compared to the 13% that NE-FVS predicted for Adirondack stands on well-buffered soils. After shelterwood harvest, stands at the TLW recovered to an average of 73% of their pre-harvest basal area, whereas the simulated Adirondack stands recovered to 36–40% of their initial basal area. This incongruence is explained by the fact that in the current study we simulated the initial cut as well as the final overstory removal, whereas the TLW experiment included only the initial cut. If we assume that half or more of the original overstory is removed during the second cut of a shelterwood harvest (Nyland, 2007), we estimate very similar recovery rates between the TLW experiment and our simulations. Recovery of SM basal area after shelterwood harvest at TLW kept pace with the recovery of basal area overall, as NE-FVS predicted for Adirondack stands on well-buffered soils. Overall stocking and stocking of SM was lower at TLW before harvest as compared to the simulated Adirondack stands. As our simulation parameters were initialized using field data, however, that disparity does not reflect an artifact of our modeling but a difference in actual site conditions between the Adirondacks and TLW.

3.2. Ecosystem services

Interactions between soil chemistry and forest management also shaped outcomes in terms of ES, or the potential benefits provided to society. As above, the model containing the soil × silviculture interaction term was the top-ranked model for 4 of the 5 potential benefits: biomass provision, sawtimber provision, greenhouse gas regulation, and fall foliage (Table 2). In each case, the top model explained at least 80% of variation in the benefit type (all $R^2_c > 0.81$).

Cumulative yields of total biomass and sawtimber after 100 years were similar under both the diameter limit and shelterwood treatments (Fig. 2), and significantly greater than under the sugarbush treatment. Yields of sawtimber and biomass were also significantly greater on well-buffered sites than on acid-sensitive sites, due largely to higher stocking on these sites in the initial inventory (2009).

After the 100-year simulation period, greenhouse gas (GHG) regulation was greater under the harvest treatments than under the unmanaged reference. This result supports the current theory that forest stands harvested for biomass will initially act as net carbon sources relative to unharvested stands (i.e., incur a "carbon debt"), but will eventually contribute to net reduction in the global carbon pool as vegetation recovers and the harvested biomass is used to substitute for fossil fuels and fossil-intensive products (Miner et al., 2014; Walker et al., 2013). On well-buffered sites, the diameter-limit harvest and shelterwood prescriptions provided a significantly greater potential GHG regulation benefit than the sugarbush, due mainly to higher production of wood products (and consequently, greater carbon use value) resulting from those treatments. Across prescriptions, GHG regulation benefits were marginally higher on well-buffered sites relative to acid-impaired sites. This suggests that slower growth and reduced stocking in acid-impaired forests stands may represent an important mechanism by which ecosystem acidification could exacerbate global climate change.

The simulated value of the fall foliage quality index in 2109 under the reference treatment was significantly less than that under the sugarbush treatment, and significantly more than under the diameter limit treatment. On acid-sensitive soils, the shelterwood treatment resulted in an index value that was not statistically different from the diameter limit treatment. On well-buffered soils, the shelterwood treatment fell between (but was not statistically different from) the diameter limit and reference treatments, in terms of the foliage quality index. Fall foliage index values under the harvest treatments were greater on well-buffered soils than on acid-sensitive soils. Overall, the value of the metric corresponded closely to SM basal area as a result of our default assumption that SM foliage was two times as preferable as the foliage of other hardwoods. We emphasize that these results are highly sensitive to our assumptions about species preferences. If we were to assume that other hardwoods are valued more highly than SM, the greatest values of the index would be found on acid-sensitive sites under the two regeneration treatments. If we were to assume that the foliage of all species is valued similarly, then the value of the index would be uniformly high across all treatments and soil conditions — deviating from 1.0 only where stands include some proportion of non-deciduous conifer species. Additional research – including that using beneficiary surveys – is needed to test our assumptions and to better characterize beneficiary preferences for the structure and composition of forests providing fall foliage and other aesthetic benefits.

For maple syrup yield, the top-ranked model included silviculture as a single term (Akaike weight = 0.702, $R^2_c = 0.675$). The second-ranked model included both silviculture and soil acidity without an interaction term (Akaike weight = 0.283). The sugarbush and unmanaged reference provided significantly higher potential yields of syrup (median = 14.870 L) compared to the diameter-limit and shelterwood treatments (median = 409 L). Potential syrup yields are lower for the harvested stands because the new cohort that develops after canopy-removal includes very few trees that grow sufficiently large (≥25.4 cm DBH) for tapping during the 100-year simulation. We found no significant difference in syrup production between the sugarbush treatment designed specifically for the production of maple sugar and the reference treatment (CI = [−2424, 4865]), which suggests that active sugarbush management may be unnecessary where SM is already the dominant canopy species.

We note that our analysis did not consider any potential effects of soil chemistry on SM sap yield or sugar content; the differences that we found in potential syrup yield between well-buffered and acid-impaired sites resulted entirely from differences in the initial stand structure, composition, and growth rates. If soil acidity reduces sap flow or sweetness directly or indirectly (e.g. through intensifying Ca deficiency) or affects the mortality or longevity of tapped trees, soil base saturation may have a significance to syrup production that our modeling approach would have been unable to elucidate. Recent research has found no connection between soil calcium and sap sweetness in forests of New Hampshire (Wild and Yanai, 2015).

3.3. Monetary valuation

We estimated that the monetary value of the ecosystem services assessed ranged between \$10,850 and \$713,800 ha^{-1} cumulatively over a 100-year period (Fig. 3). The median monetary value of the stands under the sugarbush and unmanaged treatments (\$183,605) was significantly greater than that of the stands in which we simulated regeneration harvests (\$26,136). The large difference in value observed was because nearly all (>95% under the unmanaged treatment) of the total potential monetary value of each stand is derived from syrup production (Fig. 4). Although the two regeneration harvests produce more wood products, more carbon regulation, and (in some cases) equivalent quality of fall foliage as the unmanaged and sugarbush treatments, these services are not nearly as valuable on a per-hectare basis as maple syrup production. We found no significant difference in estimated monetary value between the sugarbush and reference treatments (CI = [−\$24,046, \$59,351]), which suggests that a silvicultural intervention may not be necessary to maximize the potential economic value of these forests. Our results reflect a tradeoff between forest harvesting and syrup production that could naturally resolve itself on well-buffered soils as large SM stems reestablish in the canopy, while future syrup yields may be permanently lost on acid-impaired soils after the canopy is harvested.

Lack of empirical – or simulated – regeneration data at rotation's end made it impossible to continue our analysis over multiple rotations; therefore in this analysis we made no assumptions regarding whether or not stands would be harvested a second time after 2109. However, it is possible to estimate the total yield (standing + total harvest) of

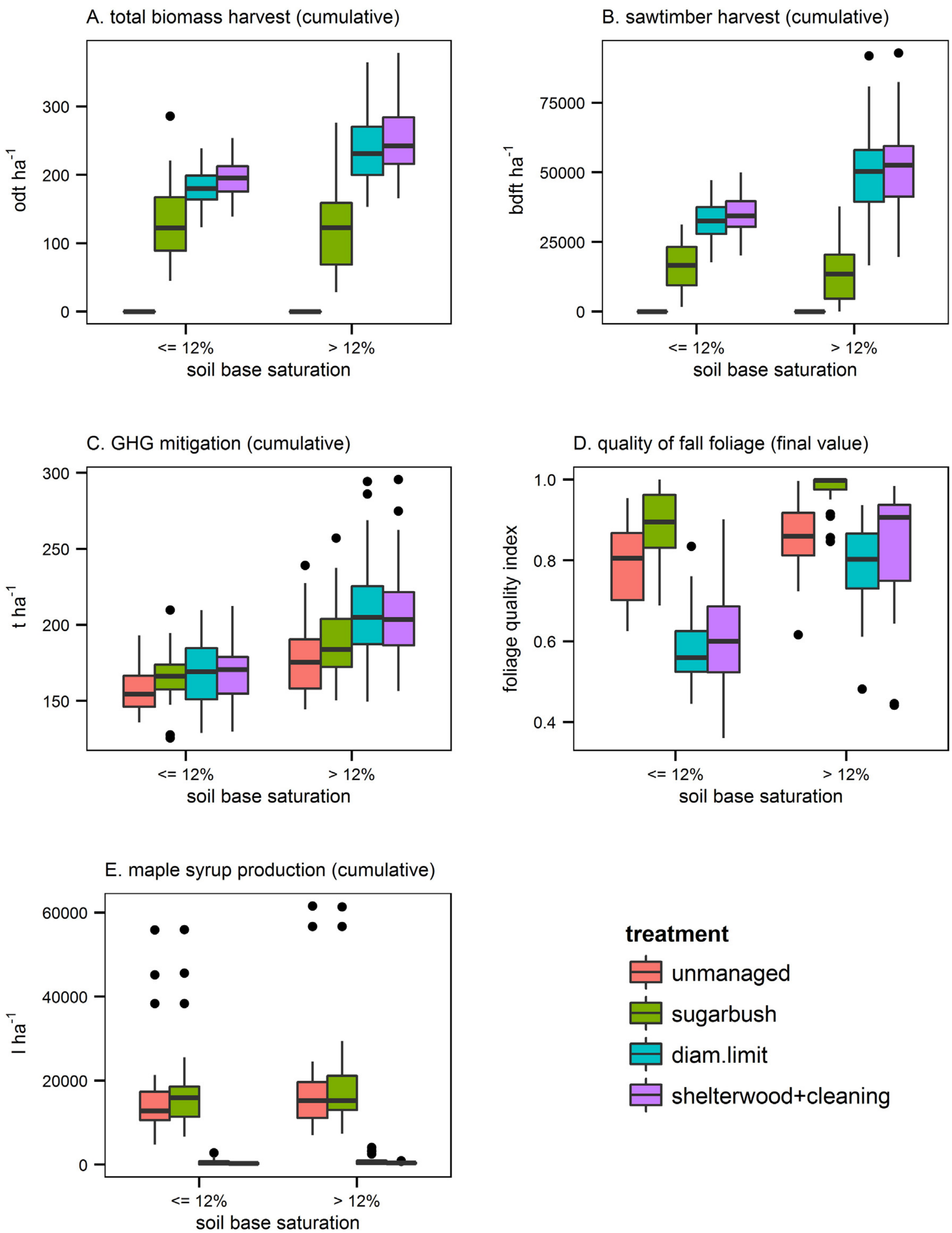

Fig. 2. Projected measures of five ecosystem services in 2109 by silvicultural treatment and soil base saturation, in 50 stands in the western Adirondack region of New York State, USA. Of the 50 stands, 26 were acidified (≤12% soil base saturation in the upper B horizon) and 24 were well-buffered (>12% soil base saturation). Each stand was simulated under each of four silvicultural treatments using NE-FVS. Boxplots are defined by the median, first and third quartiles. Plot whiskers designate the minimum and maximum values within 1.5 times the interquartile range; all points whose values fall outside this range are plotted as outliers.

biomass and wood products at this time to begin to understand the implications for long-term management of these stands (Fig. 5). The total yield of biomass was highest under the shelterwood and diameter-limit treatments and lowest under the reference treatment. On the other hand, yields of high-value sawtimber and overall gross receipts (cordwood + timber) were highest under the reference and sugarbush treatments. These results suggest that the optimal ecological rotation is equivalent to or less than our study period, while the optimal economic rotation is somewhat longer than 100 years. Although this rotation length is longer than commonly recommended for northern hardwoods (Nyland, 2007), it makes sense given the slow growth recorded for these particular stands (Bishop et al., 2015) and the fact that recorded growth rates were directly used to parameterize our model simulations.

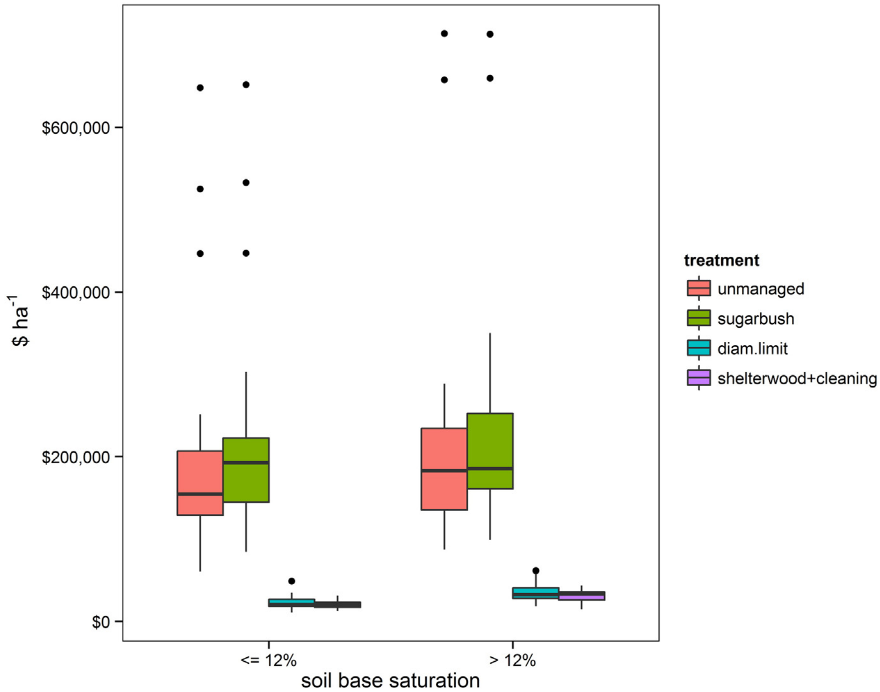

Fig. 3. Projected total combined value of ecosystem services provided by Adirondack hardwood forests by the year 2109, based on 50 stands simulated under four silvicultural treatments and two levels of soil base saturation (≤12% or >12%). Ecosystem services include provision of sawtimber and energy feedstocks, greenhouse gas mitigation, maple syrup provision, and aesthetic quality of fall foliage. Boxplots are defined by the median, first and third quartiles. Plot whiskers designate the minimum and maximum values within 1.5 times the interquartile range; all points whose values fall outside this range are plotted as outliers.

3.4. Caveats and limitations

As a first caveat, our choice to include only a single pulse of regeneration at the beginning of each scenario was dictated by the limitations of our data and the absence of a full establishment sub-model in NE-FVS. To some extent, this choice conflicts with the rationale behind the shelterwood method, in which the initial cut is intended to stimulate additional advance regeneration under a partially closed canopy (Nyland, 2007). In this respect, heavy thinning associated with the sugarbush method could resemble the initial cut in the shelterwood system, and might therefore be expected to result in similar increases in maple regeneration. It is important to keep in mind, however, that SM is a very shade-intolerant tree (Burns and Honkala, 1990), and it is primarily calcium availability – not light – that is the main factor

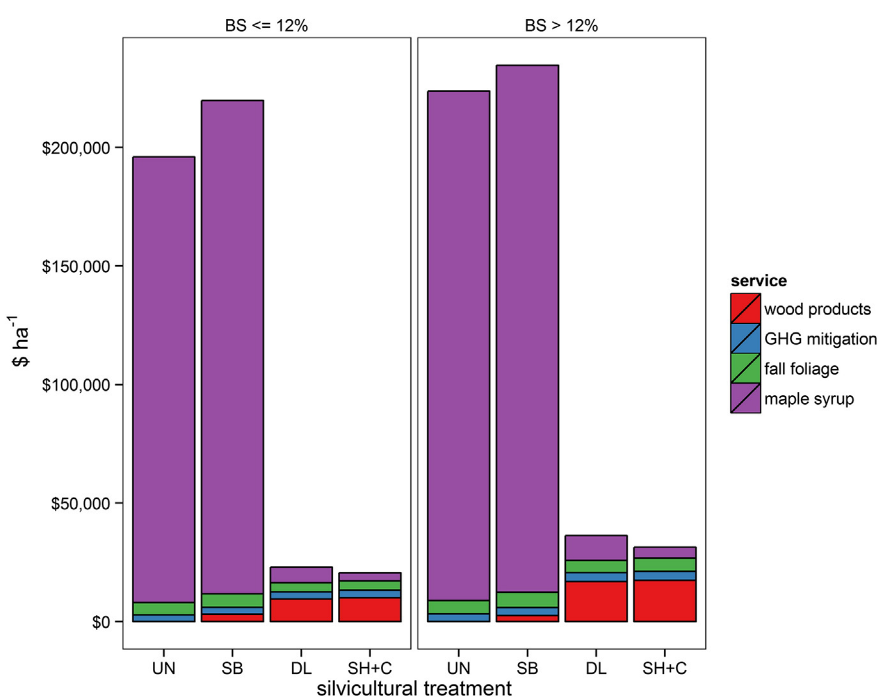

Fig. 4. Summary of cumulative projected economic values of Adirondack hardwood forests by the year 2109, based on 50 forest stands simulated under four silvicultural treatments and two levels of soil base saturation (≤12% or >12%). Silvicultural treatments include an unmanaged reference (UN), a managed sugarbush (SB), a diameter limit harvest (DL), and a shelterwood harvest with a silvicultural cleaning (SH + C).

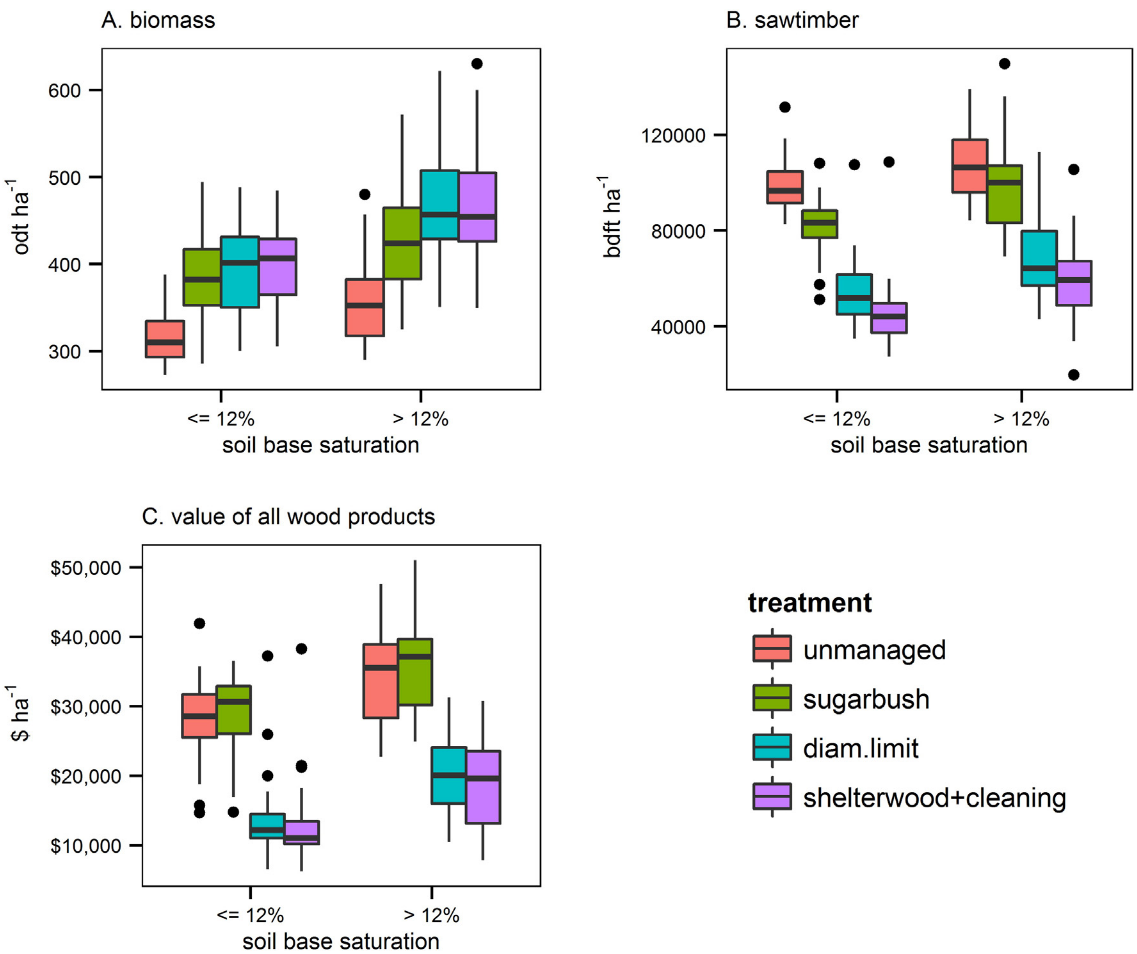

Fig. 5. Projected cumulative yields of biomass, sawtimber, and wood products value from 50 forest stands in the western Adirondack region of New York State, USA, simulated under four silvicultural treatments and two levels of soil base saturation (≤12% or >12%). Yield includes standing biomass in 2109 plus cumulative harvests during the 2009–2109 period. Boxplots are defined by the median, first and third quartiles. Plot whiskers designate the minimum and maximum values within 1.5 times the interquartile range; all points whose values fall outside this range are plotted as outliers.

limiting regeneration in this system (Sullivan et al., 2013). Where advance regeneration of SM was already low or absent in those stands with low soil base saturation, it is unlikely that opening up the canopy would result in any significant germination of new seedlings. If, on the other hand, the shelterwood method was successful in promoting successful SM regeneration – and adequate seedling survival – in acid-impaired stands, it is likely that SM would constitute a much larger proportion of the subsequent cohort than our simulations currently predict.

Second, in attaching monetary estimates to services, we estimated the total *value* of ES accruing to society as a whole. We did not estimate or attempt to estimate *revenue* (gross or net) to landowners. From the perspective of a hypothetical landowner, the production of ES may have high operational costs (e.g., syrup production), high transaction costs (e.g., carbon offsets), or limited marketability (e.g., fall foliage) — all of which would reduce net revenue. On the other hand, operational costs associated with timber harvesting are traditionally born by the loggers and downstream wood users (e.g., sawmills) in this region. In the case of the wood and fiber provisioning service, our value estimates would be expected to correspond more directly to revenue.

Lastly, we did not discount future value or assume any change in the unit value of services over time. Application of discount rates would increase the profitability of early harvests and would likely increase the profitability of harvesting wood products (which occurs early in the rotation) relative to other ES produced throughout the entire 100-year rotation. Similarly, the unit values of ES (e.g., stumpage values, carbon pricing, syrup prices) are likely to change over a 100-year period, which would affect our estimated results in unpredictable and potentially significant ways. Forecasting such changes in unit values of individual services cannot be estimated – or guessed at – with any certainty. Moreover, attempting to do so was beyond the scope of our current study.

3.5. Management implications

In general, management of forest ecosystems typically involves tradeoffs among different ecosystem services and societal values (Bennett et al., 2009; Beier et al., 2008; MA, 2005). For example, wood products provision may occur at the expense of wildlife habitat, water quality or aesthetic values. In this study, we found that tradeoffs associated with management of northern hardwood forests on acid-impaired soils are more severe – and perhaps more final – than on well-buffered soils that have been more resistant to acid pollution. Service provision and its monetary value were already marginally lower on acid-impaired sites – by an average of \$27,734 ha^{-1} – in the absence of any management intervention. But much larger decreases in service provision and estimated monetary value were evident when the high-value SM overstory was harvested on acid-impaired sites. The outcomes did not vary significantly depending on whether harvest was conducted using the shelterwood method or a diameter-limit harvest.

Our model simulations indicate that a landowner's decision whether or not to harvest the overstory in an acid-impaired forest represents a bifurcation point, i.e., a ‘fork in the road’ in terms of the system's trajectory. Either the SM can be harvested and replaced in the next cohort(s) by other species, or the SM overstory can be maintained for several more decades, perhaps with an emphasis on syrup production, GHG storage, or aesthetic values. Given enough time in this non-harvested state, soils may recover naturally – or through ecosystem restoration efforts via liming (Battles et al., 2014; Long et al., 2011) – such that sustainable harvest of SM timber may resume. We estimated potential net monetary losses from overstory harvesting in acid-impaired Adirondack forests ranged from $172,999 to $199,191 ha^{-1} when compared to the unmanaged and sugarbush treatments, respectively. Since SM constitutes one of the most important commercial sawtimber species in the northern forest and its harvest and regeneration is commonly the focus of northern hardwood silviculture, this is a decision point that is often encountered in working forests of the northeastern United States and southeastern Canada.

Several benefits provided by SM can also be provided by the other tree species that may replace it. For example, carbon sequestration and biomass production remained relatively consistent across our simulations and were not coupled with density of SM. Fall foliage of other species, particularly red maple, may have equal or greater aesthetic quality than SM foliage. Syrup can be produced from the sap of other trees, including red maple.

Our findings beg the question: how can northern hardwood forests be managed sustainably where a legacy of acid rain persists? Production of high-value SM timber may be a sustainable strategy where soils are high in base saturation and the understory contains sufficient advanced regeneration. In contrast, syrup production may be a preferable management objective on those acid-sensitive sites where lack of regeneration makes long-term sugar maple silviculture infeasible. Maple syrup represents the greatest proportion of the potential value from a mature sugar maple stand and, importantly, sap production appears to be relatively insensitive to soil acidity as long as management actions maintain or improve the number of large mature sugar maple trees. However, only a small percentage of suitable SM stems in the region are actually tapped (Farrell, 2013), and sap collection is probably not logistically or economically feasible across the large spatial extents where soil acidification has occurred in the Adirondack region (Johnson et al., 2008).

4. Conclusions

We found that the impacts of acid rain on forest ecosystems of the Adirondack region have limited the options for their sustainable management, and in turn, have reduced their potential economic and cultural values for current and future generations. The key vulnerability of these forest ecosystems – and many of their societal benefits – hinges on the sensitivity of SM to the acidification and depletion of calcium from poorly buffered forest soils. SM is an ecological keystone of the northern hardwood forest and is among the most economically and culturally significant tree species in eastern North America. We have shown that forestry practices that were developed specifically to sustain high-value species such as SM for future rotations may no longer have successful outcomes in severely acid-impaired ecosystems.

Model simulations of forest stand dynamics revealed that interactions between soil acidification and silvicultural prescriptions may fundamentally shape the future species composition and long-term provision of goods and services from northern hardwood forests. While the simulated provision of ES was marginally lower from acidified forests than well-buffered forests, we found that much more significant acid-mediated differences emerged in response to management practices that remove the existing overstory. Mean losses of up to $214,099 ha^{-1} over a 100-year period were estimated as a result of this interaction. Although careful silviculture (e.g., shelterwood method) can be successful in regenerating SM stands on well-buffered (non-acidified) soils, the establishment of new SM cohorts on acidified soils is unlikely, regardless of whether stands are managed using recommended silvicultural practices or harvested using the diameter-limit approach. This suggests that the SM overstory currently found on acidified soils represents an ecological legacy from a period before soil acidification reached critical levels. Removal of this overstory would likely constitute the last commercial SM harvest before the stand composition shifts to become dominated by the much lower-valued red maple and American beech. Because poorly-buffered forest soils are expected to take centuries to fully recover from acidification, this compositional shift – and the associated consequences for valued ecosystem services – represents a long-term legacy of acid rain.

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