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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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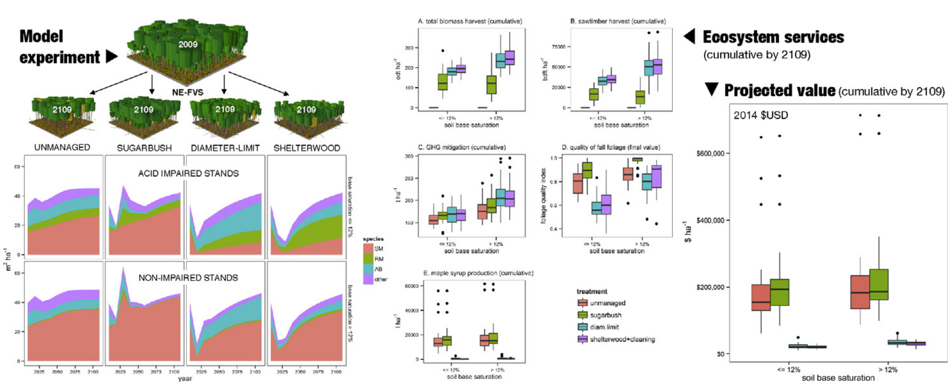
HIGHLIGHTS

- 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.