Variation in Forest Soil-Nutrient Availability: Dynamic Model Estimates of Past and Future Conditions at Two Sites in the Daniel Boone National Forest, Kentucky, USA

Final Report

Prepared for:
USDA Forest Service

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June 28, 2019

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ACKNOWLEDGEMENTS

This research was supported by a contract between E&S Environmental Chemistry, Inc. and the USDA Forest Service. This report has not been subjected to agency review and no agency endorsement is implied.

ABSTRACT

Tree harvesting on soils with low nutrient pools is a consideration in forest management on public lands in the southeastern United States. This study evaluated the effect of future tree harvesting on soil nutrient base cation supply in the context of recovery from historical nitrogen (N) and sulfur (S) deposition at two locations within the Daniel Boone National Forest. A dynamic biogeochemical model was used to evaluate changes in soil and soil solution chemistry from the pre-industrial times to several centuries into the future. Model results indicated that pre-industrial (year 1850) base cation supply was ten times higher than recent observations. The historical decline in soil base saturation can be attributed largely to elevated atmospheric N and S deposition caused by electricity generation from coal fired power plants. Recovery from soil base cation depletion at the model sites is not expected for several hundreds of years, even if N and S deposition are reduced from ambient levels. Future tree harvesting on base depleted sites on the Daniel Boone National Forest will further degrade soil base status at these model sites, which are characterized by low soil mineral base cation weathering rates to resupply nutrients for tree uptake and buffer against mobilization of toxic inorganic aluminum.

1 INTRODUCTION

Calcium (Ca), magnesium (Mg), and potassium (K) are important forest soil base cation nutrients (collectively Bc) that also influence the acid-base status of surface drainage water.

They, along with sodium (Na) and acid cations aluminum (Al) and hydrogen (H), contribute to the soil base saturation, which controls the soil acid-base status. The effects of tree harvesting on Bc pools and fluxes is of concern in forest management on public lands in the southeastern United States, many of which have inherently low weathering supplies of Bc to soil surfaces and have experienced Bc depletion in response to elevated acidic deposition since the Industrial Revolution. Demand for soil Bc to support forest growth has been emerging as an increasing important forest land management concern (Löfgren et al. 2017).

We estimated, using a dynamic biogeochemical model, effects of different forest management scenarios on Bc budgets relative to soil Bc supplies in the context of sustainable forestry. Tree growth affects the acid-base status of forest soils, largely because trees accumulate Bc from soil solution (Olsson et al. 1993, Aherne et al. 2008). There may be an increasing move towards use of tree harvest residues (slash) after harvesting as biofuels, in place of fossil fuels, in support of climate policies (Aherne et al. 2008). Increasingly intensive tree harvesting will cause increased export of nutrients, including Bc, that will have a similar impact on the forest ecosystem as does acidification caused by acidic deposition (Sverdrup and Rosen 1998). Effects of acidic deposition on soils has been documented at many low-base sites in Appalachia (Bailey et al. 2005, Farr et al. 2009, Lawrence et al. 2015b). Highly weathered, low-base soils in this region are susceptible to Bc depletion.

Current forest harvesting practices in many portions of this region are typically stem-only (SOH); leaves, branches, and coarse roots are left on site after logging. However, biofuels from slash debris might provide useful alternatives to fossil fuels. A shift to whole-tree harvesting (WTH) in the future to meet a growing need for biofuels would provide an enhanced drain on Bc soil pools and fluxes to streamwater in these forests. Non-merchantable timber biomass can be harvested for energy production in the form of tree branches, tops, stumps, and in rare cases roots. These are converted to chips at the site of production, at the roadside, or at the site of use for energy production. Combustion of biofuels can play a role in mitigating climate change, although such combustion can be in conflict with some environmental protection goals (Aherne et al. 2012). Chemical mass balance studies have suggested that WTH can enhance nutrient depletion of forest soils (Joki-Heiskala et al. 2003, Aherne et al. 2008).

Acidic deposition was high throughout much of the 20th century in the southeastern United States, but has decreased over the past several decades. Soil and drainage water acidification recovery in response to reduced emissions and deposition of S, and to a lesser extent nitrogen (N), can be counteracted by acidification caused by forest re-growth after harvesting.

Decreased emissions and deposition of S over the past several decades has caused decreased sulfate (SO_4^{2-}) leaching to surface and ground water (Sullivan 2017). This decreased SO_4^{2-} leaching is charge-balanced, in part, by decreased leaching of Bc (Garmo et al. 2014) and accumulation of Bc weathering (Bc_w) products on negatively charged soil exchange sites (Lawrence et al. 2015a, Löfgren et al. 2017). Continued future acidification or recovery from past acidification will be partly determined by management choices that are made regarding where and how to harvest timber and other forest biomass (Belyazid et al. 2006, Moldan et al. 2013).

Nutrient limitation and deficiency and their effects on soil productivity are important to silvicultural practices and govern the response of reduced levels of acidic deposition to long-term forest productivity. Large nutrient removals via intensive tree harvesting, especially WTH, is of concern to the forestry industry because of potential long-term declines in soil fertility and availability to vegetation of cations on soil exchange sites (Rothstein 2018).

Harvesting of forest biomass can affect the chemical quality of soils and surface waters by removing Bc and N. Such nutrient losses are balanced by atmospheric N and Bc deposition and Bc_w (Sverdrup and Rosen 1998, Akselsson et al. 2007, Aherne et al. 2012). These processes are further impacted by changes in temperature and precipitation. Dynamic hydrogeochemical models, such as the Very Simple Dynamic (VSD) model (the updated version of which is referred to as VSD+) and others, can be used to evaluate impacts of acidification, harvesting, and climate change, individually or cumulatively and to evaluate effects associated with future scenarios.

Soil Bc pools are critical for healthy vegetation and aquatic and terrestrial biota. Previous harvesting of timber has contributed to periodic loss of Bc from forested sites throughout the southeastern United States. Long-term acidic deposition has accelerated Bc loss in this region (Sullivan et al. 2004). This Bc loss has been particularly problematic for forests with acid-sensitive soils (McDonnell et al. 2013).

In 1994, baseline soil acid-base conditions were established using soil and lysimeter (soil water) sample measurements at two poorly-buffered ridgetop locations on the Daniel Boone National Forest (DBNF), Kentucky, USA (Barton et al. 2002). Resampling at the same locations in 2012 and 2013 suggested degraded soil quality during the intervening period even though atmospheric sulfur (S) deposition had decreased markedly (Sanderson et al. 2017). Questions remain regarding the potential impact of combined future timber harvesting and acidic deposition on long-term soil productivity and vegetation health. In addition, vegetation management strategies might help achieve resource management objectives that include protecting the supply of Bc on the soil cation exchange sites. The use of a biogeochemical model is one method to evaluate these issues and associated questions.

The objective of the research described here was to apply the VSD+ biogeochemical model to assess how acidic deposition and timber harvesting combine to affect soil Bc supplies in DBNF. Results will inform USDA Forest Service decisions regarding the feasibility of sustained timber harvesting where historical acidic deposition has been high and has caused depletion of Bc from the soil.

This report provides application of VSD+ to two small generally acid-sensitive ridgetop locations in DBNF using available data on soil and soil chemistry, atmospheric deposition, watershed characteristics, climate, and tree nutrient uptake. The primary objective was to assess the extent of soil Bc depletion associated with historical acidic atmospheric deposition and the effects of future timber harvesting scenarios on soil Bc supply.

The biogeochemical environmental effects model VSD+ was applied to address the following questions:

- How will soil properties respond to varying levels of timber harvesting and acidic deposition in data-rich, acid-sensitive areas in DBNF?
- Will soil properties improve with additional declines in acidic deposition? If improvement can occur without liming, how long will it take to achieve desired soil properties?
- What is the extent to which Bc fertilization (i.e. liming) is needed to facilitate achievement of desired soil properties?

2 APPROACH

The VSD+ model predicts long-term changes in soil acid-base chemistry in response to acidic deposition and other disruptions of Bc supply and cycling. The model focus is on the pools of exchangeable Bc and the soil pH (Posch and Reinds 2009, Bonten et al. 2016). The

VSD+ model balances annual changes in net nutrient uptake by vegetation, N and carbon (C) immobilization, nitrification, denitrification, and Bc inputs via deposition and Bc_w. Geochemical interactions such as cation exchange on the soil are included. Hydrogen ion concentration is calculated as the sum of measured anions minus cations, except H^+ (Zeng et al. 2017).

Earlier studies by Barton et al. (2002) and Sanderson et al. (2017) investigated effects of acidic deposition on soil and soil solution chemistry in DBNF. They found evidence that acidic deposition has depleted soil Bc, resulting in low base saturation and soil pH and high exchangeable soil acidity. Sanderson et al. (2017) previously collected soil and soil solution samples on ridge tops in DBNF in McCreary and Wolfe Counties, Kentucky, to evaluate possible effects of acidic deposition on soils. Two sites were studied. They were generally low in base saturation and pH and high in exchangeable acidity.

Combustion of low-S coal, together with addition of emissions control technology and market forces that have driven a shift from coal towards oil and gas for generating electrical power, have contributed to lower emissions and deposition of S, and to a lesser extent N, over the last few decades (cf., https://nadp.slh.wisc.edu/). Soil recovery from previous acidification has generally been modest in the eastern United States (cf., Warby et al. 2009), and this is partly attributable to long-term depletion of soil Bc reserves (Likens et al. 1996).

2.1 Study Area

The DBNF is located in parts of central, eastern, and southeastern Kentucky and includes parts of Clay, Estill, McCreary, and Wolfe counties. The land is characterized by mixed hardwood forest over steep ridges and narrow ravines. It has a temperate climate with moderately cold winters and warm, humid summers and receives about 121 cm of annual precipitation and winds mostly from the south and west. The forest is comprised of nearly

300,000 ha of federal land along with inholdings of residential, private forest, and farm lands. It is located in proximity to urban and industrial land uses and dozens of coal-fired power plants in Kentucky and surrounding states (Sanderson 2014), many of which are located generally upwind of the forest. The two sites (Wolfe and McCreary) investigated here are situated on ridgetops of the Cumberland Plateau (**Figure** 1).

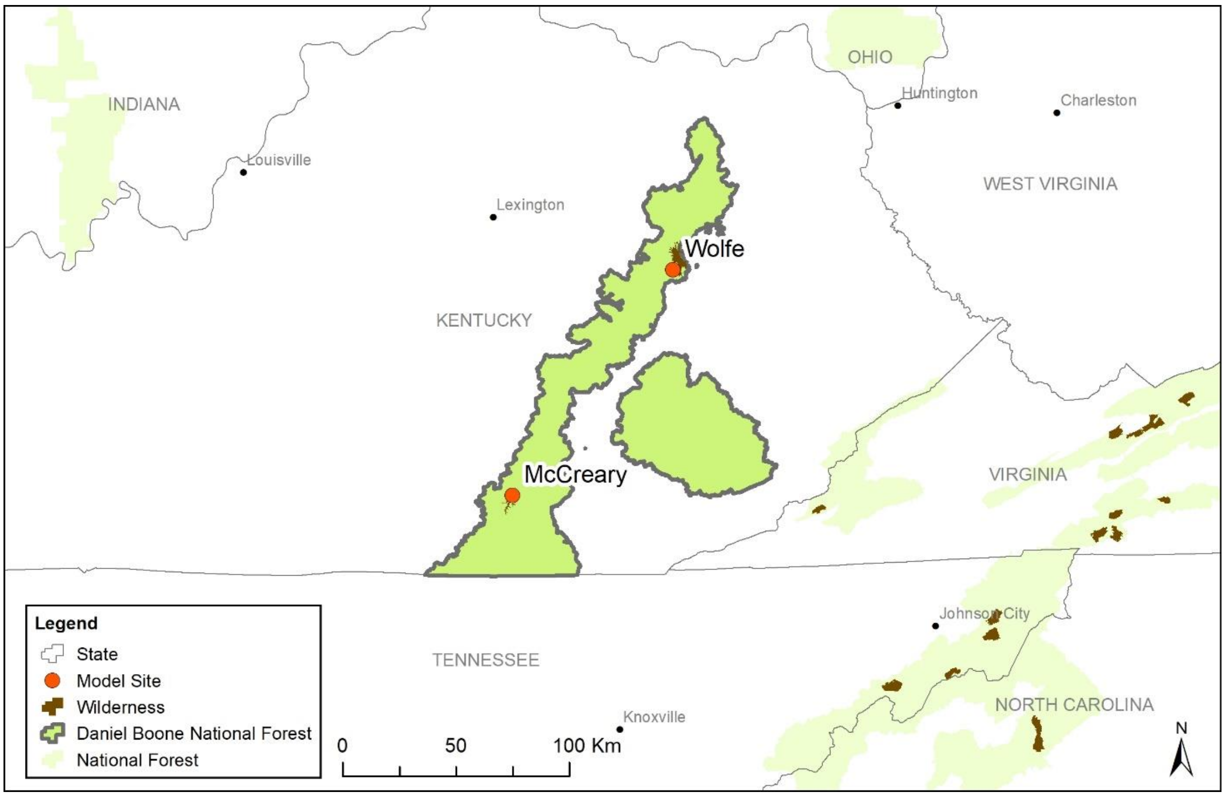

Figure 1. Location of VSD+ model sites on the Daniel Boone National Forest.

2.2 Model Application

The VSD+ model requires estimates of site-specific parameters related to climate, atmospheric deposition, soil conditions, and nutrient cycling. Most of these data were readily available for this study. In some cases, sub-models and pre-processors were needed to develop the required VSD+ inputs. These included the PROFILE model (Sverdrup and Warfvinge 1993) for determining Bc weathering rates, MetHyd (Bonten et al. 2016) for hydrological inputs, and GrowUp (Bonten et al. 2016) for determining nutrient uptake and litterfall rates.

The original VSD Model was described in detail by Posch and Reinds (2009). The VSD model was based on charge and mass balances in soil solution and included atmospheric deposition, mineral weathering, litterfall input to the soil, and vegetation uptake. The pH of soil solution was calculated from the concentrations of other elements. Sinks and sources of the various elements were specified and reflected in chemical concentrations in water discharge.

The VSD+ model incorporates improvements to the earlier VSD model, including simulation of turnover in organic C and N (Posch and Reinds 2009). Variations in the soil organic C pool are simulated using the RothC-26.3 model of Coleman and Jenkinson (2014), a five-compartment soil model that represents decomposable plant material, resistant plant material, microbial biomass, humified organic matter, and inert organic matter (Bonten et al. 2016). The model has been applied at sites in Sweden and Germany (Bonten et al. 2016) and the northeastern and southeastern United States (McDonnell et al. 2018).

2.2.1 Input Data and Calibration

Available tabular and geospatial data were obtained and formatted for model input. Soil physiochemical data and mineralogy were gathered from Barton et al. (2002) for the two model sites. Historical and current climate conditions related to temperature and precipitation were obtained from PRISM (http://www.prism.oregonstate.edu/). Historical reconstructions of total N, S, and Bc deposition were developed with data from the Total Deposition Science Committee (TDEP; Schwede and Lear 2014) of the National Atmospheric Deposition Program (NADP), Advanced Statistical Trajectory Regional Air Pollution (ASTRAP; Shannon 1998) model, Baker (1991), and interpolated NADP wet deposition (http://nadp.sws.uiuc.edu/ntn/maps.aspx).

Historical timber harvesting in the year 1927 at Wolfe and in 1932 at McCreary was simulated (C. Cotton personal communication). Bark beetle infestation at the McCreary site in the year 2000 was also represented in the hindcast simulations. Additional details regarding model inputs used in this study data can be found in **Appendix A**. Information regarding minimum data collection requirements for model application at other locations is included in **Appendix** B.

Peak N and S deposition of approximately 20 kg N/ha/yr and 30 kg S/ha/yr was estimated to occur in the early 1970s (**Figure** 2). Ambient (3-year average of 2014-2016) S deposition is approaching assumed background levels and ambient N deposition remains about nine times higher than assumed background levels.

Observed soil base saturation values (Barton et al. 2002) were used to calibrate cation exchange coefficients using a Bayesian approach performed with a Markov chain Monte Carlo method (Reinds et al. 2008). Additional soil and soil water chemistry data measured by Barton et al. (2002) and Sanderson et al. (2017) were used to compare historical trends reproduced by the calibrated model.

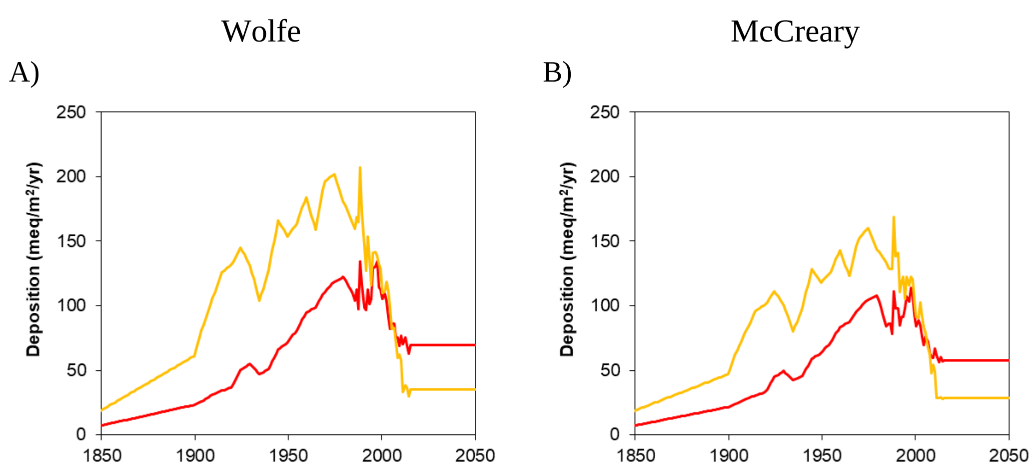

Figure 2. Historical reconstructions of N (red line) and S (orange line) deposition at the A) Wolfe and B) McCreary model sites. Future deposition was held constant at ambient levels.

2.2.2 Future Scenarios

A set of five model scenarios to describe potential future rates of atmospheric deposition (**Figure** 3) and timber harvesting practices were implemented (**Table** 1). Additionally, the extent of elevated Bc inputs (i.e. liming) needed to restore and maintain base saturation from current (year 2016) to pre-industrial (year 1850) levels was determined.

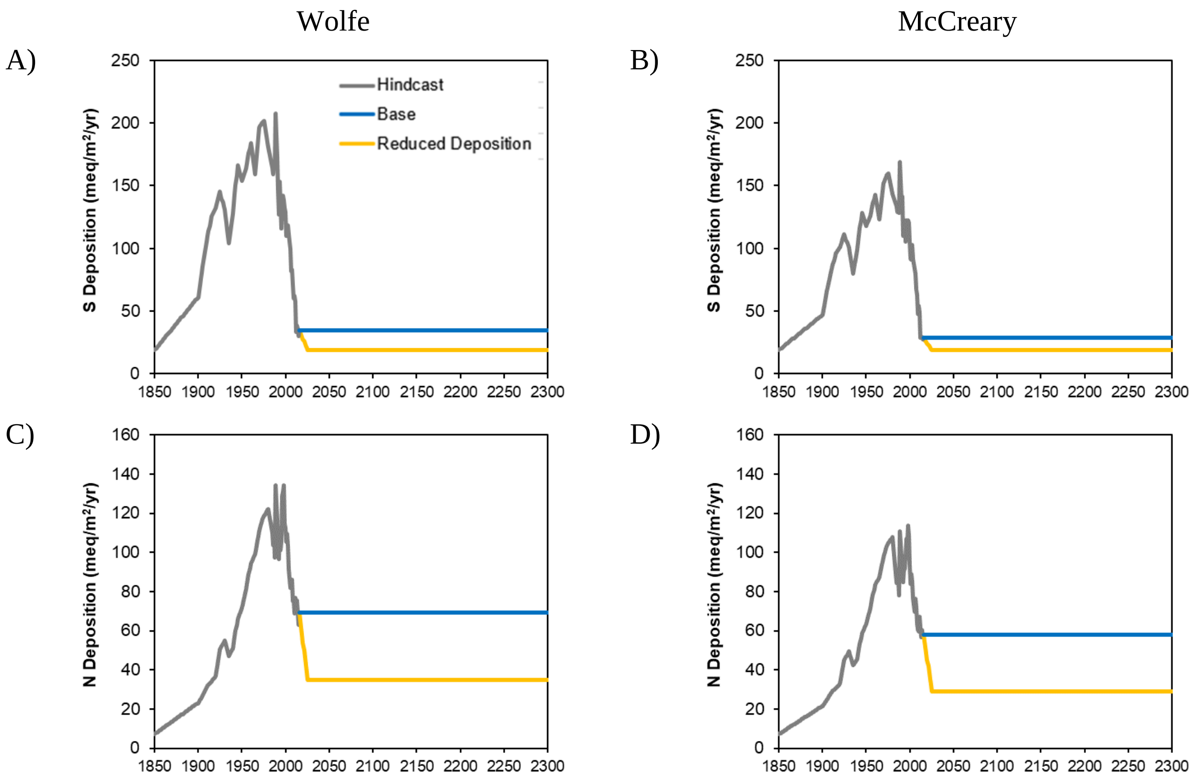

Figure 3. Simulated hindcast and future S and N deposition scenarios at the Wolfe (panels A and C) and McCreary (panels B and D) model sites.

Table 1. Future scenarios simulated with VSD+ at the Wolfe and McCreary model sites.

Scenario Name	Simulated Future (2016 – 2300) N and S Deposition	Simulate Future Harvesting
Base	Constant N and S deposition at ambient (3-year average 2014-2016) levels	None
Reduced Deposition	50% reduction in N deposition (relative to ambient levels) and a reduction in S deposition to background levels (3 kg S/ha/yr)	None
25% Stem Removal	Constant N and S deposition at ambient (3-year average 2014-2016) levels	Remove 25% of stem biomass. Leaves, branches, and roots remain on-site.
50% Stem Removal	Constant N and S deposition at ambient (3-year average 2014-2016) levels	Remove 50% of stem biomass. Leaves, branches, and roots remain on-site.
75% Stem Removal	Constant N and S deposition at ambient (3-year average 2014-2016) levels	Remove 75% of stem biomass. Leaves, branches, and roots remain on-site.

3 RESULTS AND DISCUSSION

3.1 Comparisons with Observed Data

Overall, the VSD+ model was able to generally reproduce observed soil and soil solution chemistry at the Wolfe and McCreary model sites. Simulated soil base saturation was in close agreement with observations for the calibration year at both sites (**Figure** 4). More recent observations of soil base saturation were somewhat underestimated at Wolfe and were in close agreement at McCreary. The modeled trend in soil solution SO_4^{2-} and nitrate (NO_3^-) concentrations generally corresponded with average observations (**Figures** 5 and 6). However, simulated soil solution SO_4^{2-} concentration was underestimated at McCreary in comparison with the two years of data following insect infestation. The soil sampling by Sanderson et al. (2017)

did not occur in the exact locations as the samples used by Barton et al. (2002), which may have contributed differences between simulated data and data observed by Sanderson et al. (2017).

3.2 Hindcast Scenario

Elevated historical N and S deposition has resulted in extensive soil Bc depletion at both model sites (**Figure** 4). Pre-industrial soil base saturation was estimated to be in the range of 40 – 50% at both model sites, which is approximately 10 times higher than recent observations. This result is not surprising given that the extent of historical N and S deposition this region is among the highest that has occurred in the United States. Soil pH was also estimated to have decreased to levels that could promote dissolution of toxic inorganic aluminum in soil water (results not shown), which increases the risk of detrimental impacts to tree root growth and aquatic communities of local drainage waters. Although current levels of S deposition are substantially lower than peak levels, soil water SO_4^{2-} concentrations remain relatively high (**Figure** 5) due to desorption of previously adsorbed SO_4^{2-} from soil anion exchange sites. Temporary spikes in soil solution NO_3^- concentration were associated with simulated disturbance events (tree harvesting and insect infestation) which reduce tree N uptake and allows for atmospherically deposited N to remain in soil solution (**Figure** 6). These relatively short-lived increases in soil solution NO_3^- concentration were suppressed as N uptake increased with tree regeneration. Increases in soil base saturation associated with Bc inputs from decomposed post-disturbance tree biomass remaining on-site are also apparent (**Figure** 4).

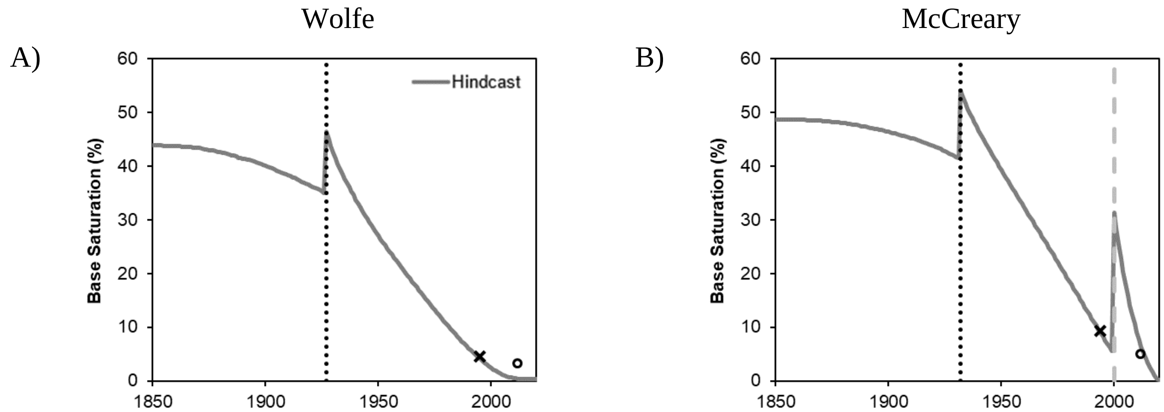

Figure 4. Simulated hindcast (1850 – 2020; solid line) soil base saturation at the A) Wolfe and A) McCreary model sites along with observed data used for calibration (cross) and comparison (open circle). Years in which tree harvesting (dotted line) and insect infestation (dashed line) were simulated are also shown.

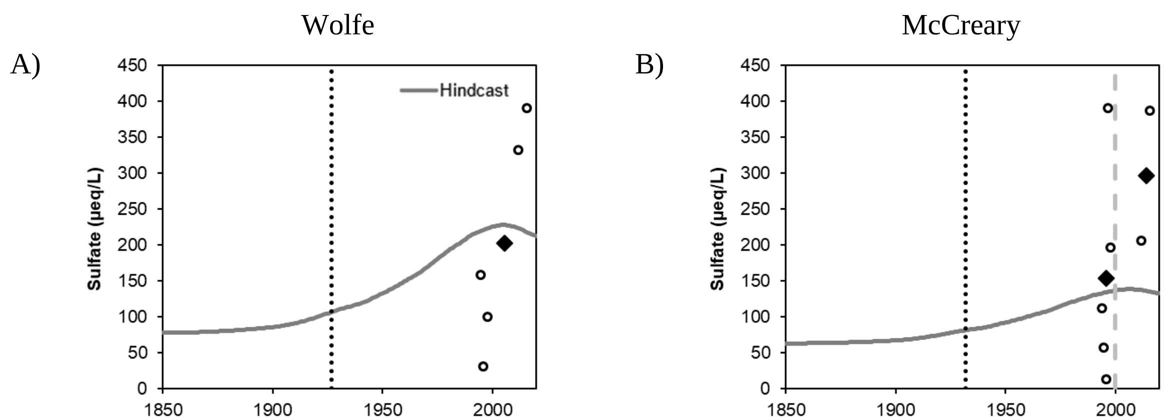

Figure 5. Simulated hindcast (1850 – 2020; solid line) soil solution sulfate concentration at the A) Wolfe and B) McCreary model sites along with average annual observed data (open circle) and an average among all observations (black diamond; for McCreary, this was split between pre- and post- insect infestation). Years in which tree harvesting (dotted line) and insect infestation (dashed line) were simulated are also shown.

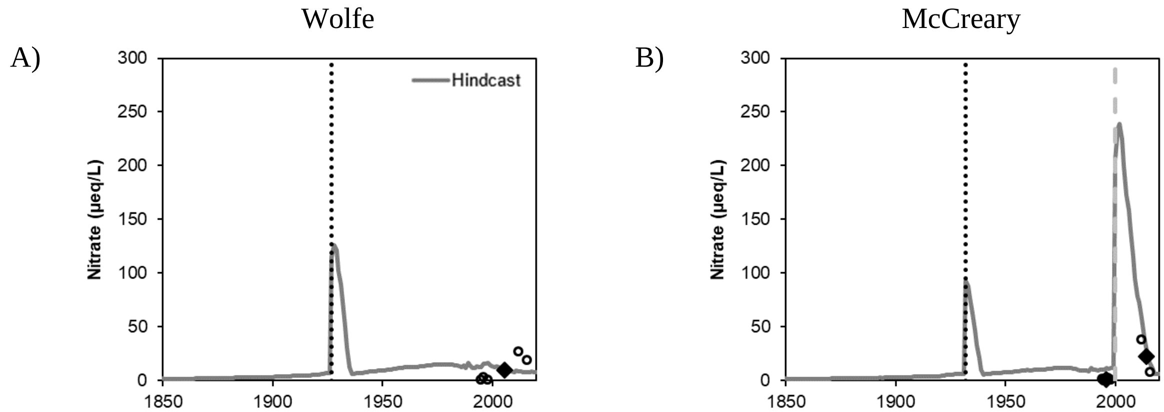

Figure 6. Simulated hindcast (1850 – 2020; solid line) soil solution nitrate concentration at the A) Wolfe and B) McCreary model sites along with average annual observed data (open circle) and an average among all observations (black diamond; for McCreary, this was split between pre- and post- insect infestation). Years in which tree harvesting (dotted line) and insect infestation (dashed line) were simulated are also shown.

3.3 Future Scenarios

3.3.1 Deposition

Under the base scenario, soil pH increased by approximately 0.5 and 0.75 pH units at Wolfe and McCreary, respectively (results not shown), by the year 2300 and was accompanied by slight increases in soil base saturation at both sites (**Figure** 7). Marginal gains (+3%) in soil base saturation were simulated under the reduced deposition scenario at both sites. Lower levels of future S deposition associated with the reduced deposition scenario are expected to result in slightly lower future soil water SO_4^{2-} concentrations (**Figure** 8). Soil solution NO_3^- concentrations at Wolfe increase near the end of the base scenario simulation period as N uptake by trees decreases (**Figure** 9). However, reduced future N deposition is expected to maintain low soil solution NO_3^- levels throughout the simulation period at Wolfe. Tree uptake of N at McCreary is expected to be sufficient to maintain low soil solution NO_3^- concentration throughout the simulation period under both the base and reduced deposition scenarios.

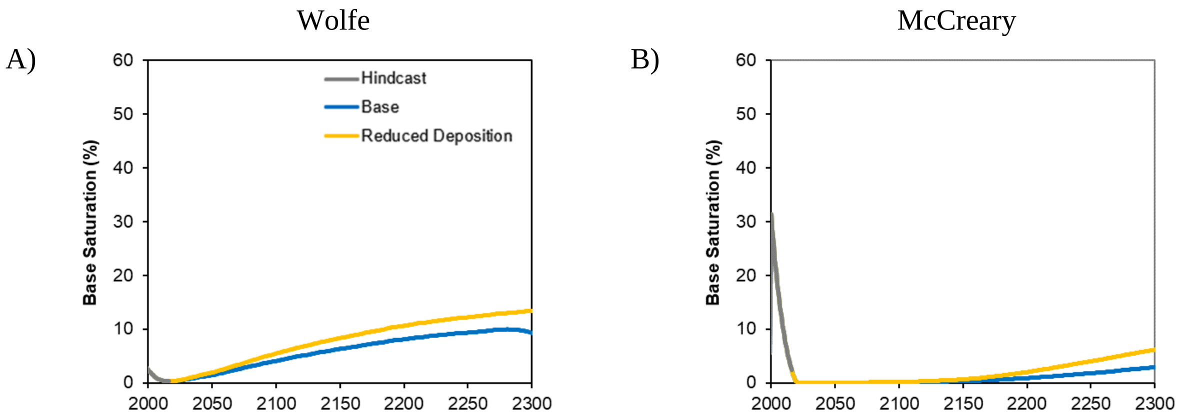

Figure 7. Simulated deposition scenario results for soil base saturation at the A) Wolfe and B) McCreary model sites.

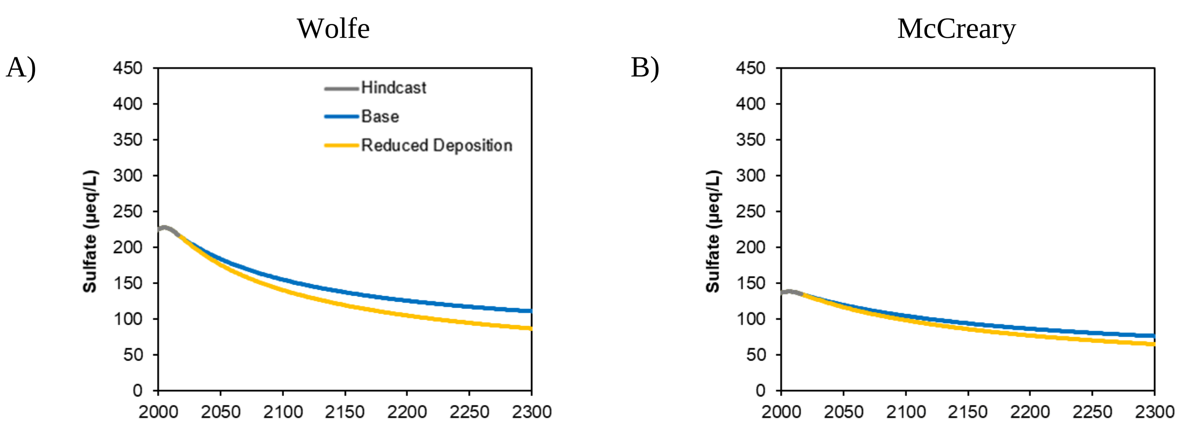

Figure 8. Simulated deposition scenario results for soil solution sulfate concentration at the A) Wolfe and B) McCreary model sites.

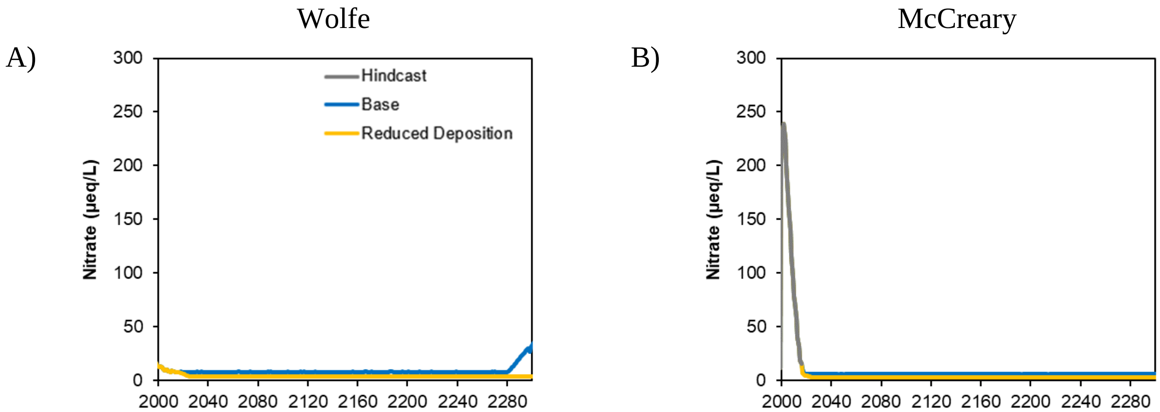

Figure 9. Simulated deposition scenario results for soil solution nitrate concentration at the A) Wolfe and B) McCreary model sites.

Soil Bc supply could be restored with the addition of lime or other Bc containing soil amendments. The current rates of Ca deposition at Wolfe and McCreary are 3.4 and 2.8 kg Ca/ha/yr, respectively. Under the base scenario, the annual rates of additional Bc input that would be needed to increase and maintain soil base saturation at pre-industrial levels until year 2300 are approximately 24 kg Ca/ha/yr and 14 kg Ca/ha/yr at Wolfe and McCreary, respectively.

3.3.2 Tree Harvest

Short term dynamics in soil base saturation were simulated subsequent to simulated future harvesting at both sites. This was attributable to increased Bc supply from decomposition of logging residues and increased soil solution N associated with decreased N uptake (**Figure** 10). Long-term trends indicated that soil base saturation associated with the various harvest scenarios would be suppressed relative to the base (no harvest) commensurate with the extent of logging. The magnitude of these decreases in soil base saturation are expected to be significantly lower than the soil Bc depletion associated with historical atmospheric N and S deposition. The

Wolfe McCreary

A)   B)

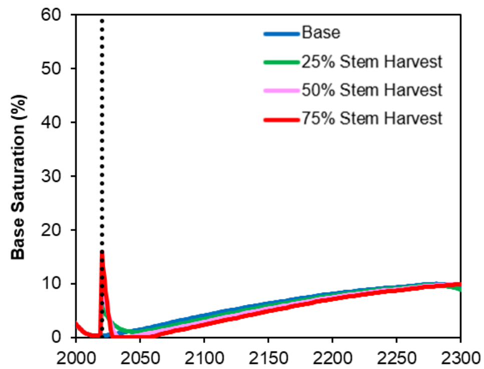

Figure 10. Simulated harvest scenario results for soil base saturation at the A) Wolfe and B) McCreary model sites. Years in which tree harvesting (dotted line) was simulated are also shown.

model simulated recovery from previous soil acidification and future Bc depletion associated with harvesting.

Model results suggested that soil Bc pools at the modeled sites have become depleted, thereby negatively impacting tree growth and water quality. Furthermore, a future shift from SOH to WTH on the study sites would pose a risk of increasing nutrient deficiency in soil and continued soil acidification. Eventually, forest fertilization might be needed to restore Bc availability to support sustainable forestry.

Akselsson et al. (2007) showed that the effects of WTH were more pronounced on spruce, compared with pine, forests in Sweden due to higher growth rates, higher Bc content of foliage, greater quantity of slash, and low weathering in the soil underlying spruce stand. Mass balance calculations for Swedish spruce and pine forests by Akselsson et al. (2007) further suggested that WTH caused substantially higher losses of K and Ca as compared with SOH. They concluded that such Bc losses might contribute to negative effects on soil fertility and tree vitality and growth. Stem-only harvesting caused less impact on K pools, but depletion of Ca and Mg was substantial with both WTH and SOH.

Akselsson and Belyazid (2018) concluded that the contribution of tree harvesting to soil acidification and Bc depletion has increased in recent years in Sweden because the impacts from atmospheric S deposition have decreased and the demand for energy from biofuels has increased. Therefore, they recommended development of new policy tools for evaluating recovery from past soil acidification as the basis for informed forest management in the future. A shift from SOH to WTH in the DBNF would likely slow recovery from past soil acidification and Bc depletion.

Iwald et al. (2013) estimated that the soil acidification caused by WTH of spruce could be 114 to 263% of that caused by acidic deposition in Sweden. The effect of WTH of pine was somewhat less (57 to 108%). Based on these and other findings, Akselsson and Belyazid (2018) judged that WTH of spruce stands in southern Sweden is not sustainable unless nutrients, especially Ca, are added to the soil. A similar situation may exist for the DBNF.

Aherne et al. (2008) used the Model of Acidification of Groundwater in Catchments (MAGIC) to estimate the responses of 163 lake watersheds in Finland to past, ambient, and future acidic deposition in conjunction with current SOH and a switch to WTH. This was based on a possible future switch to WTH to increase use of biofuels. They found that the ambient SOH practices were close to the sustainable maximum harvesting under legislated acid precursor emissions controls in Finland.

4 CONCLUSIONS

Ridgetop locations, and likely other areas, of the DBNF have experienced extensive soil Bc depletion as a result of historical N and S deposition mostly originating from electricity generation from coal fired power plants. Given the relatively low rates of soil Bc weathering, simulated future decreases in N and S deposition are expected to allow only marginal recovery in soil base status in the coming centuries. As such, full recovery to pre-industrial base saturation in these locations is not expected for many hundreds of years. Although future harvest scenarios representing a single harvest of 25%, 50%, and 75% of stem biomass further reduced soil Bc supply, these decreases were minimal relative to the extent of impact from historical N and S deposition. Additional harvesting beyond the single simulated event and/or a shift to WTH would be expected to further suppress soil nutrient Bc supply at low-base sites in DBNF towards zero. Measurements of soil base saturation and cation exchange capacity represent the minimum information needed to use the VSD+ model in different locations.

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APPENDIX A. MODEL INPUTS

Base Cation Weathering

In order to develop base cation weathering input data for the VSD+ modeling, the computer program A2M (Posch and Kurz 2007) was used with total element (oxide) data to predict quantitative mineralogy; based on results of this analysis, observed feldspar mineralogy was allocated to K-feldspar (0.25) and Plagioclase (0.75) in PROFILE. This quantitative mineralogy was then allocated to PROFILE mineral classes; base cation weathering rates for Wolfe and McCreary soils from Barton et al. (2002) were estimated using PROFILE (Table A-1). Additional inputs for PROFILE were derived from observations used in the VSD+ modeling (climate, runoff, and precipitation chemistry, as described below) or estimated from default values (pCO_2, K_{gibb}, soil solution DOC) expected to be representative of soil conditions at the model sites (Mapping Manual 2004).

Table A-1. PROFILE estimated weathering rates based on observations for the Wolfe and McCreary sites. These values were used as input to VSD+.

County	Year	Depth (cm)	Coarse Fragments (%)	Surface (m^2/m^3)	LOI* (%)	Bulk Density (g/cm^3)	Sum BC (eq/ha/yr)	Ca (eq/ha/yr)	Mg (eq/ha/yr)	K (eq/ha/yr)	Na (eq/ha/yr)
Wolfe	1994	58.2	3.1	3296213	1.87	1.296	543	18	209	256	60
McCreary	1994	56.6	5.8	2916161	1.66	1.312	331	2	161	160	8

* LOI is loss on ignition

Hydrology and Reduction Factors

The MetHyd pre-processor model was used to develop reduction factors for modeling mineralization, nitrification, and denitrification and for developing soil water content and runoff estimates (precipitation minus evapotranspiration) as inputs for VSD+ (Bonten et al. 2016). Results from MetHyd were applied using soil texture and organic matter content estimates from

Barton et al. (2002) in conjunction with long-term trends in precipitation derived from PRISM data (http://prism.oregonstate.edu/) and incoming solar radiation from (New et al. 2002).

Forest Nutrient Cycling

The GrowUp tool (v1.3.2; Bonten et al. 2016) and Forest Vegetation Simulator (FVS; Crookston and Dixon 2005, Keyster 2015) were used in conjunction with known historical disturbance events (i.e., tree harvests, insect infestation) to derive VSD+ inputs related to nutrient base cation and N uptake and litterfall for model calibration. GrowUp input requirements include:

- biomass data related to nutrient content, density, turnover rate, and biomass expansion factor (BEF; multiplication factor used to expand stem volume to account for non-merchantable biomass components including branches, coarse roots, fine roots and foliage),
- stem volume growth according to a logistic growth curve, and
- disturbance events.

Default biomass data for oak and pine trees were used for all three sites, except for stem tissue nutrient contents and stem turnover rates. Stem tissue nutrient content was specified based on measured values (C. Barton personal communication, May 30, 2018). The stem volume was calculated as:

$$V_{(t)} = \left(V_{(t-1)} + Gr_{max} * \frac{V_{(t-1)}}{(K_{gr}+V_{(t-1)})}\right) * (1 - k_{turnover})$$

where $V_{(t)}$ and $V_{(t-1)}$ are the standing stem volumes at, respectively, time *t* and at the previous time step *t*-1 (m^3 ha^{-1}); Gr_{max} is the maximum growth rate (m^3 ha^{-1} yr^{-1}); K_{gr} is the 'half velocity' growth constant (i.e. the stem volume at which the tree species reaches half of its maximum growth rate; m^3 ha^{-1}); and $k_{turnover}$ is the turnover rate, which is the fraction of stem volume that falls down in a year. Estimated growth is based on the Monod (1949) equation.

Stem growth characteristics were derived from growth profiles produced by the FVS model (Crookston and Dixon 2005), which simulates growth of a forest inventory sample. It considers effects of insects, pathogens, fire, fuel loading, snag dynamics, and development of understory tree vegetation. Growth profiles used in the analysis reported here depict natural growth (i.e., undisturbed) represented by the Southern variant FVS model based on FIA forest inventory data (Keyser 2015; Chad Keyser, U.S. Forest Service, personal communications, December 17, 2015 and February 17, 2016). Growth profiles were generated for a set of FIA forest groups which were paired with the VSD+ model sites according to the dominant overstory vegetation. The Pitch Pine/Virginia Pine/Hardwood FVS growth profiles were used for modeling forest growth at both sites.

Within the GrowUp tool, the initial stem volume in the year 1850 ($V_{(0)}$) was assumed to approximate the steady-state condition (i.e., mature forest) and Gr_{max} was determined directly from the FVS growth data. The stem turnover rate ($k_{turnover}$) and K_{gr} were fitted to the FVS growth data.

Known historical disturbance events were simulated. One tree harvest event was included as an assumed 80% removal of aboveground biomass at Wolfe and McCreary in the years 1927 and 1932, respectively (C. Cotton, personal communication, May 14, 2018). An insect infestation that resulted in 90% tree mortality at McCreary in the year 2000 was also included. All dead biomass was retained on-site subsequent to major disturbance events. The availability of observed soil solution nitrate allowed for adjusting the extent of N uptake following this disturbance to correspond with observations.

Atmospheric Deposition

All atmospheric deposition inputs were determined as annual total (wet + dry) deposition. The baseline N deposition value for 1850 was assumed at a level of 1.0 kg N/ha/yr according to recent Clean Air Status and Trends Network (CASTNet) and National Atmospheric Deposition Program (NADP) measured values for Alaska (https://www.epa.gov/castnet; http://nadp.sws.uiuc.edu/) and model baseline estimates by Holland et al. (1999). Baseline S deposition was based on the analyses of Husar et al. (1991; 3.0 kg S/ha/yr). The Advanced Statistical Trajectory Regional Air Pollution (ASTRAP; Shannon 1998) model and interpolated NADP monitoring data (http://nadp.slh.wisc.edu/) were used to specify wet N and S deposition for years 1900 – 1980 and 1985 – 1999, respectively. Linear interpolation was used to fill any gaps among available years of data. The dry:wet deposition ratios for N and S (3-year average centered on 2001) were derived from the Total Deposition (TDep) atmospheric deposition modeling (Schwede and Lear 2014). These ratios were applied to the wet deposition from ASTRAP and NADP to generate total N and S deposition for the years 1900 to 1999. Total N and S deposition from TDep was used to specify deposition for the years 2000 to2015. Future N and S deposition was held constant at levels assocated with the 3-year average ambient level centered on 2014. Base cation deposition was derived from Baker (1991) and held constant for the full simulation period.

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APPENDIX B

For application of VSD+, much of the input data can be derived from publicly available databases analogous to those described for the application described in this report. In addition, site measurements of soil exchangeable base cation (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}) and acidity (H^{+} and Al^{3+}) are needed along with a method for estimating soil mineral base cation weathering. Multiple methods exist for estimating base cation weathering, including:

1) Clay-substrate method (Umweltbundesamt (UBA) 2004)
    a. Estimates of soil percent clay and knowledge of the underlying lithology are needed to implement the clay-substrate method. This method can be used anywhere, but is the most unreliable.
2) Extracted from MAGIC model calibrations (McDonnell et al. 2012)
    a. Measurements of full ion chemistry in stream drainage water plus soil chemistry are needed. This method works best for estimating base cation weathering for watershed soils draining relatively small catchments with thin soils.
3) Estimated using the PROFILE model (Sverdrup and Warfvinge 1993)
    a. Measurements of total soil oxides and a qualitative description of minerals present are needed for this method. This method is the most reliable.

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