Effects of Climate, Land Management, and Sulfur Deposition on Soil Base Cation Supply in National Forests of the Southern Appalachian Mountains

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Abstract Forest soils having low exchangeable calcium (Ca) and other nutrient base cation (BC) reserves may induce nutrient deficiencies in acid-sensitive plants and impact commercially important tree species. Past and future depletion of soil BC in response to acidic sulfur (S) deposition, forest management, and climate change alter the health and productivity of forest trees. This study used a process model (Model of Acidification of Groundwater in Catchments [MAGIC]) to address a number of questions related to soil BC status for a group of 65 streams and their watersheds in the southern Blue Ridge physiographic province of the southern Appalachian Mountains. Future S deposition to the study watersheds used for the Base Scenario was specified according to proposed reductions in S emissions at the time of this study, representing a reduction of 42 % of ambient S deposition by 2020.

Twenty additional simulations were considered, reflecting four alternate S deposition scenarios (6 %, 58 %, 65 %, and 78 % reduction), and various changes in timber harvest, temperature, and precipitation. Base Scenario soil exchangeable Ca and % base saturation showed decreasing trends from 1860 to 2100. Changes in tree harvesting had the largest effect on stream sum of base cations (SBC) and soil BC supply. Each of the scenario projections indicated that median year 2100 soil exchangeable Ca will be at least 20 % lower than pre-industrial values. The simulations suggested that substantial mass loss of soil BC has already occurred since pre-industrial times. Nearly the same magnitude of BC loss is expected to occur over the next 145 years, even under relatively large additional future reductions in S deposition.

Keywords Base cation · Acidification · Forest productivity · Appalachian Mountains · MAGIC

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1 Introduction

The forested terrestrial and aquatic resources of the Blue Ridge Province of the southern Appalachian (SA) Mountains have provided, and continue to provide, valuable ecosystem services to the American people. The SA Mountains have the largest diversity of plant species in the temperate forest region, and some of these species have been utilized for medicinal, cultural, wood products, and other purposes. The forests provide habitat for numerous terrestrial and aquatic wildlife, with some species

considered rare or endangered. The SA Mountains also constitute an important source of drinking water for many communities in the region.

Forest soils within the high elevations of the SA region have developed from the slow breakdown of parent rock material that can be inherently low in base cations (BC), including calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na; Elwood et al. 1991). Combustion of fossil fuels and agricultural production within and upwind of the SA region contribute acidic sulfur (S) and nitrogen (N) deposition to SA forests. These intrinsically low soil BC pools have become further depleted as a result of BC leaching to drainage water in response to acidic deposition that began in the mid-1800s and increased to peak values in the early 1990s. Deposition levels have subsequently decreased over the past two to three decades (Greaver et al. 2012) in response to the Clean Air Act (CAA) and its amendments. Negative effects of low soil BC supply on tree growth and health in the SA Mountains and elsewhere have been documented (Elias et al. 2009; Lovett et al. 2009). Partly as a consequence of past land management and acidic deposition, soil BC depletion now poses a threat to sustainable forest productivity within the region (Elias et al. 2009; Huntington 2000).

Ecosystem sensitivity to acidification and the effects of acidic deposition on surface water quality and nutrient status of forest soils have been well studied in this region, especially at the high elevations (Baker et al. 1990a, b; NAPAP 1991; Sullivan et al. 2004; Johnson et al. 1993, 1999; Elliott et al. 2008). Hydrogen and aluminum (Al) ions replace BC lost to leaching from soil cation exchange sites. The BC mobilized and leached to drainage waters leave soils with depleted stores of nutrient cations. Forest ecosystems within the SA mountains have been shown to be especially sensitive to Ca depletion (Huntington 2000). Soils with decreased exchangeable Ca and other BC reserves may induce nutrient deficiencies in acid-sensitive plant species and cause adverse effects on both commercially important tree species and understory plants. Depletion of soil Ca and increases in available Al in response to acidic deposition have altered the health and productivity of forest trees (Schaberg et al. 2006; Long et al. 2011; Halman et al. 2011).

Trees remove nutrient BC (Ca, Mg, K) from the soil and incorporate them into biomass though uptake and assimilation. After a tree dies, these BC are returned to the soil though decomposition and mineralization, making them available for tree uptake. Because of this internal cycling, it can be assumed that there is little or no net loss of BC from the soil in an unmanaged and unimpacted forest over the long term. However, harvesting of trees in the SA region, with removal of wood from the site, has permanently removed some nutrient BC from biogeochemical cycling at many locations. A variety of factors affect the magnitude of this BC removal, including species, growth rate, and harvest rotation length. The majority of tree BC are stored in tree boles and it has been estimated that tree harvest in the SA region can remove between 7.7 and 25.5 meq/m^2 of nutrient BC per year (McNulty et al. 2007). However, reduced tree growth in response to any stressor is expected to decrease BC uptake into vegetation (Grier et al. 1989; Högberg et al. 2006).

Other factors can also influence soil BC pools and base saturation (BS), such as ongoing change in the climate of the SA Mountains. There is considerable uncertainty, however, regarding the extent to which air temperature or precipitation may change in the future at any given location. If long-term precipitation decreases, then increased drought frequency could reduce forest productivity (Hanson and Weltzin 2000; Gholz et al. 1991) and leaf longevity (Jonasson et al. 1996). Under water stress, there is increased potential for insect infestation (Mattson and Haack 1987), fire (Flannigan et al. 2000), and tree mortality (Kloeppel et al. 2003). Increased temperature can increase evapotranspiration, contributing to water stress on trees and reduced subsurface water flow to streams (Mitchell et al. 1990; Rosenberg et al. 1990). A large majority of stream flow in forested watersheds originates from water routed through subsurface soils and delivered to streams. The amount of water that moves through the soil profile affects the rate at which BCs are leached from soil exchange sites. An increase in precipitation and subsurface flow will result in higher BC leaching. The opposite effect will occur under lower flow regimes.

An increase in the long-term ambient air temperature can also increase or decrease forest productivity (McNulty and Boggs 2010). Higher temperature may result in a longer growing season, allowing for increased biomass production. In contrast, increased air temperature could increase evapotransporation and result in water stress causing a negative effect on growth even if precipitation remains the same. Furthermore,

each tree species contains a unique set of nutrient uptake and environmental requirements to maintain its presence on a site (McNulty et al. 2007; Iverson et al. 2008). Nutrient cycling effects might occur if tree species composition changes in response to future changes in climate.

An understanding of the historical loss of soil BCs and expected future base status of soils under various climate, management, and S deposition scenarios is needed by forest managers responsible for maintaining healthy and productive forests in this region. The principal objectives of the study reported here were to use the Model of Acidification of Groundwater in Catchments (MAGIC; Cosby et al. 1995) for a group of 65 streams and their watersheds in the southern Blue Ridge physiographic province of the SA Mountains to address a number of questions related to soil BC status, including:

- What has been the historical rate of soil BC loss due to leaching in response to anthropogenic S deposition?
- How will decreases in the amount of acidic deposition affect soil BC concentrations in the future?
- Can S deposition be reduced to a level that will allow soil BC pools to recover from historical BC losses?
- What is the expected effect of a changing climate on future soil BC status?
- How will changes in timber harvesting affect soil BC status?
- What amount of BC fertilization will be needed to restore BC pools and recover ecosystem services?

This study is unique among previous applications of MAGIC in the SA region because it is focused on soil condition as it relates to forest health and productivity rather than stream chemistry and associated effects on aquatic biota. Additionally, changes in drivers of BC supply other than S deposition are included in model scenarios. These drivers of BC supply can interact to compound or negate effects and such interactions are addressed. However, the primary objective was to evaluate the potential drivers on an individual basis. The focus of this study was on relatively acid-sensitive watersheds within the SA region. These watersheds are thought to be generally representative of the surrounding national forest land area where forest management actions may be required in order to partly or fully recover historical BC pools and prevent future loss of soil BC caused by continued elevated atmospheric S deposition, as influenced by changes in climate.

2 Methods

2.1 Study Sites

The study sites included 65 watersheds for which data were available for calibrating the MAGIC model within the Cherokee, Nantahala, Pisgah, and Sumter National Forests (Fig. 1). These forests are located in the SA Mountains within the Blue Ridge physiographic province. Modeled sites and calibration data were described in the modeling study of Sullivan et al. (2011). At least one watershed was modeled in three of the four federally mandated (according to the CAA amendments of 1977) Class I areas that occur within the study region (Joyce Kilmer-Slickrock, Linville Gorge, and Shining Rock Wilderness) as well as the Class II areas, Ellicott Rock, Middle Prong, Sampson Mountain, and Southern Nanatahala Wilderness. Class I areas receive the highest level of federal protection from air pollution degradation.

Potential modeling sites were pre-screened to remove from consideration streams having high concentration of chloride (Cl⁻; >70 μeq/l) that could have been caused by road salt application, and streams having high concentrations of NO_3^- (>30 μeq/l) that could have been caused by agricultural or silvicultural fertilization within the watershed. The potential for such anthropogenic disturbance, other than air pollution, was determined by examination of stream chemistry and location of roads, wilderness areas, and agricultural or forestry operations within the watersheds. One site included in the earlier study (Sullivan et al. 2011) was deleted from consideration in this study because of evidence that the modeled stream received geological contributions of S. Samples were also pre-screened to remove sites for which the observed percent mineral soil base saturation (% BS) was >60 %. Such high values of % BS probably represent a sampling or analysis error, or reflect a local (and unrepresentative) heterogeneity in the geology and/or soil matrix at the sampling site (Sullivan et al. 2011).

Land cover in the 65 watersheds is forested, with no agriculture or urban development. Dominant vegetation consists of mountain balds, northern hardwoods, and northern red oak communities. Spruce–fir communities can be found at high elevation (>1,060 m) with hemlock and mixed oak–pine forests occurring at lower elevation. The geology is predominantly granite, sandstone and other rock types that exhibit relatively
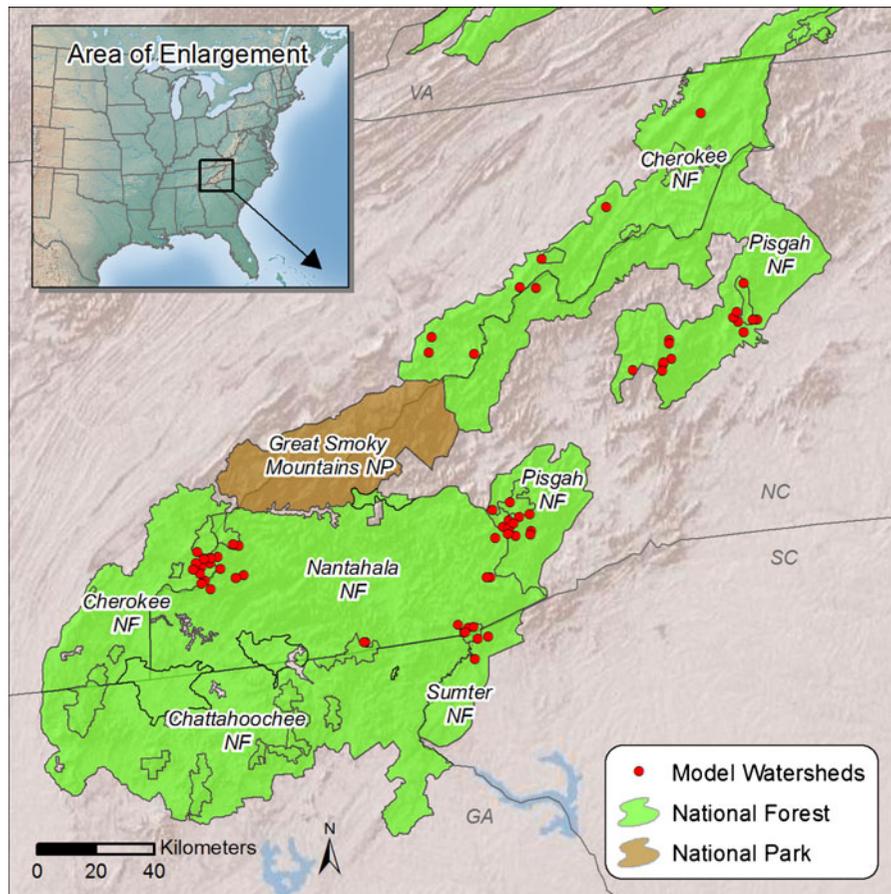
Fig. 1 Map showing study area and location of modeled sites

low BC weathering (Sullivan et al. 2007) and soils are generally shallow (<1 m; NRCS 2010).

2.2 MAGIC Calibrations

MAGIC predicts the long-term effects of acidic deposition and land management on soil and surface water chemistry. A central component of MAGIC is the pool of exchangeable BC on the soil. As the fluxes to and from this pool change over time due to changes in atmospheric deposition and/or removal via timber harvest, the chemical equilibria between soil and soil solution shift to simulate changes in drainage water chemistry. The influence of naturally occurring organic acids on stream chemistry is included in the model as a triprotic analogue (Driscoll et al. 1994), although there is no provision in the model for changes in organic acidity over time.

The validity of the model has been confirmed by comparison with estimates of surface water acidification inferred from paleolimnological reconstructions (Jenkins et al. 1990; Wright et al. 1994; Sullivan et al. 1996) and with the results of several experimental watershed acidification and de-acidification experiments (e.g., Wright and Cosby 1987; Cosby et al. 1995, 1996; Moldan and Wright 1998). MAGIC has been used to reconstruct the history of acidification and to simulate future trends on a regional basis and in a large number of individual catchments in both North America and Europe (e.g., Lepistö et al. 1988; Hornberger et al. 1989; Cosby et al. 1990; Jenkins et al. 1990; Wright et al. 1994; Sullivan et al. 2008).

The aggregated nature of the model requires that it be calibrated to observed data from a watershed before it can be used to examine potential system response. Calibration is achieved by specifying the values of fixed parameters within the model that can be directly

measured or observed. The model is then run using observed and/or assumed atmospheric and hydrologic inputs. Simulated stream water and soil chemical criterion variables are compared to observed values. If the observed and simulated values differ, the values of another set of parameters in the model (called "optimized" parameters) are adjusted to improve the fit. After a number of iterations, the simulated-minus-observed values of the criterion variables usually converge to zero, within some specified tolerance. The model is then considered calibrated and can be used for hindcasting and future scenario modeling. Because estimates of fixed parameters and deposition inputs are subject to uncertainties, a "fuzzy optimization" procedure is implemented during the calibration process. It involves multiple calibrations using random values of the fixed parameters drawn from the observed possible range of values and random values of deposition from a range including uncertainty about the estimated values. Each calibration begins with random selection of values of fixed parameters, deposition, and starting values of the optimized parameters. The optimized parameters are then adjusted using the Rosenbrock (1960) algorithm to achieve a minimum error fit to the target variables. This procedure is undertaken ten times. The final calibrated model is represented by the ensemble of parameter and variable values of the ten calibrations. Projections are reported based on the results derived from the median calibration. The acid–base chemistry modeling for this project was conducted using 2005 as the base year, as this was the year for which the input data were available. MAGIC was calibrated to the available atmospheric deposition, soil chemistry, and water chemistry data and then interpolated or extrapolated to yield base year estimates of stream water chemistry in the year 2005, which served as the starting point for each future scenario.

MAGIC scenario modeling was conducted to estimate the effects on soil chemistry of a variety of future S deposition, management, and climatic conditions. It involved 21 different scenarios, including one Base Scenario and 20 scenarios that altered future conditions. The Base Scenario was run under current management and climate regimes with a reduction in S deposition reflective of current emissions regulations that have been proposed to be phased in by the year 2020. Each of 19 of the additional scenarios modified only one aspect of the Base Scenario in an attempt to isolate the potential effects of future change in either S deposition, stream flow, forest productivity, tree har-

vest rate, or tree harvest area as described below and in Table 1. One final scenario was implemented as a representation of aggressive management, involving the maximum reduction (78 %) in atmospheric S deposition considered here and allowing no harvest on any land. Results of this scenario reflect the extent of improvement in BC supply that might be achievable by aggressively managing S emissions and timber harvest.

2.3 Hindcast Simulations

The MAGIC model was used to develop a hindcast simulation reflecting how stream and soil chemistry were expected to have responded to historical changes in S deposition over the period 1860 to 2005. The Advanced Statistical Trajectory Regional Air Pollution Model (ASTRAP; Shannon 1998) was used to provide historical estimates of wet, dry, and cloud deposition of sulfur and nitrogen oxide in and around the study region using a nearest-neighbor approach that included correction for elevation, as described by Sullivan et al. (2004). Shannon (1998) produced wet, dry, and cloud deposition estimates of sulfur and nitrogen oxides every 10 years starting in 1900 and ending in 1990. The model outputs were smoothed estimates of deposition roughly equivalent to a 10-year moving average centered on each of the output years. To estimate total deposition from wet deposition, the wet, dry, and cloud deposition estimates provided by ASTRAP for each year were used to calculate dry plus cloud deposition enhancement factors (DDF) for each year and each site. This provided time series of DDF for sulfur and nitrogen oxides for each site extending from 1900 to 1990. These were combined with linear estimates of changes in deposition between 1860 and 1900 from assumed background values. The value of DDF for 1990 was used as the absolute value of DDF for the reference year and was assumed to remain constant in the future.

At high elevation, the inputs of ions from cloud water can be large. In the SAMI project (see Sullivan et al. 2002a, b, 2004), high elevation sites in the Great Smoky Mountain National Park (GSMNP) were determined to have DDF values (reflecting dry and cloud, but particularly cloud water inputs) that were approximately twice as large as those specified by the ASTRAP model. Accordingly, Sullivan et al. (2004, 2011) used the larger DDF values for any site over

Table 1 Description of scenarios simulated using the MAGIC model for this study

Type	Scenario ID	Value	Description
Deposition	Dep4	Title IV (−6 %)	6 % reduction in 2005 sulfur deposition
	Base	Base (−42 %)	42 % reduction in 2005 sulfur deposition
	Dep1	Scen. A (−58 %)	58 % reduction in 2005 sulfur deposition
	Dep2	Scen. B (−65 %)	65 % reduction in 2005 sulfur deposition
	Dep3	Scen. C (−78 %)	78 % reduction in 2005 sulfur deposition
Climate: Productivity	Clm2	−15 %	Large decrease in forest productivity (−15 %)
	Clm1	−5 %	Small decrease in forest productivity (−5 %)
	Base	Base (ambient)	No change in productivity
	Clm3	+5 %	Small increase in forest productivity (+5 %)
	Clm4	+15 %	Large increase in forest productivity (+15 %)
Climate: Stream flow	Clm6	−10 %	Large decrease in stream flow (−10 %)
	Clm5	−4 %	Small decrease in stream flow (−4 %)
	Base	Base (ambient)	No change in stream flow
	Clm7	+4 %	Small increase in stream flow (+4 %)
	Clm8	+10 %	Large increase in stream flow (+10 %)
Management: Harvest Area	Mng1	None	No tree harvesting
	Base	Base (suitable)	Tree harvesting in suitable areas
	Mng2	Non-wild	Tree harvesting in suitable and unsuitable non-wilderness areas
	Mng3	All	Tree harvesting in suitable, unsuitable, and wilderness areas
Management: Removal	Mng4	0 %	Remove 0 % of bark and bole
	Mng5	45 %	Remove 45 % of bark and bole
	Base	Base (65 %)	Remove 65 % of bark and bole
	Mng6	85 %	Remove 85 % of bark and bole
	Mng7	100 %	Remove 100 % of bark and bole

1500 m elevation. In this project, the five sites that were over 1500 m elevation were assigned the higher DDF values used by Sullivan et al. (2004). The hindcast was performed using BC uptake rates as described for the Base Scenario below.

2.4 Future Base Scenario

2.4.1 Sulfur Deposition

The future rate of S deposition to the study watersheds used for the Base Scenario was specified according to proposed reductions in S emissions at the time of this study, as described by Sullivan et al. (2011). Base scenario deposition represents a reduction of 42 % of ambient S deposition phased in between 2010 and 2020, followed by constant deposition from 2020 to the end of the simulation period in 2150.

2.4.2 Forest Management

Some of the study watersheds on National Forest ownership exist largely within areas that are designated as suitable for tree harvest. Suitable land includes areas for which timber harvest (typically bole-only) is allowed according to the land management plan for a particular national forest. Timber harvesting was simulated in all watersheds that contained suitable land (n=33). Removal of BC from harvesting was approximated with a 65 % biomass (bark and bole) harvest rate and estimated species-specific BC uptake rates between 7.7 and 25.5 meq/m^2/year (McNulty et al. 2007).

Simulations of timber harvesting in the Base Scenario only occurred for those portions of the watershed classified as suitable for timber harvesting. The forest land management plans also include other national forest ownership designated as unsuitable for timber harvesting. These include areas designated as

wilderness and other areas designated as unsuitable for reasons identified in the forest plan. For example, the Pisgah and Nantahala land management plan lists unsuitable lands that have one or more of the following characteristics:

- The site has threatened, endangered, or sensitive species, and proposed site impacts may affect species viability.
- The site cannot be adequately restocked (regenerated) with a new stand of trees.
- Access is not possible due to terrain and/or state and/or private ownership patterns.
- Unique habitats such as seeps, bogs or rock outcrops exist.
- The area has been designated to occur within the riparian management area.
- Special uses such as power line corridors and access right of ways exist.

2.4.3 Climate

Future changes in air temperature and precipitation patterns are expected to occur globally. It is anticipated that temperatures will increase in the SA mountain region. However, there is uncertainty regarding whether the long-term annual precipitation will increase or decrease (Karl et al. 2009). MAGIC can account for changes in temperature or precipitation by adjusting the simulated forest productivity and stream flow rates. For the Base Scenario, forest productivity and stream flow were assumed to remain constant at values consistent with ambient conditions.

2.5 Alternate Future Scenarios

2.5.1 Sulfur Deposition

Four alternate future S deposition scenarios were considered (Table 1). One scenario (Dep4) included a smaller reduction (6 % decrease relative to year 2005) in S deposition than the expected changes based on proposed emissions control policy. Each of the other three deposition scenarios reflected further reductions in S deposition beyond those expected to occur in response to proposed emissions control policy (Dep1, Dep2, and Dep3). These scenarios represent 58 %, 65 %, and 78 % reduction, respectively, in ambient S deposition compared to reference year (2005) deposition, phased in

between 2010 and 2020, with constant deposition assumed from 2020 to the end of the simulation period.

2.5.2 Forest Management: Biomass Removal Rate

Potential future tree removal rates were selected to bracket the Base Scenario rate of 65±20 %, with scenarios of 45 % and 85 % removal. Two additional scenarios represented extreme tree removals of 0 % (no removal) and 100 % (removal of all bark and bole; Table 1) from all land considered suitable for timber harvest.

2.6 Forest Management: Land Management Classification

Under current forest management practices, the Base Scenario simulated harvesting only on the land area that is considered to be suitable for harvesting by the U.S. Forest Service. Occasionally, timber harvesting in unsuitable areas outside of a wilderness may occur because of large-scale tree mortality caused by a severe storm event, drought (Kloeppel et al. 2003), insect infestation (Mattson and Haack 1987) or disease outbreak. Tree harvest in these situations is typically described as a salvage operation. It should be noted that under current policies the U.S. Forest Service is unlikely to conduct any timber harvesting or salvage operations in designated wilderness areas of the SA Mountains.

The unsuitable and wilderness areas are commonly found at the highest elevations or ridge tops and can be sensitive to BC removal resulting from acidic deposition. In this study, tree BC removal due to timber harvest was simulated to estimate effects of harvesting on only the suitable lands. The alternative future scenarios based on land management classification included (1) no harvest on any land (equivalent to 0 % biomass removal listed above), (2) harvest on both suitable and non-suitable land, and (3) harvest on all forest areas including wilderness (the extreme case).

2.6.1 Climate: Productivity

The Intergovernmental Panel on Climate Change (IPCC) estimated that average global surface temperature will likely rise by 2 °C to 6 °C above 1990 levels by 2100 (IPCC 2007). The spatial distribution of the projected warming is uncertain, and some areas may

even exhibit a cooling pattern. Further, the effects of a warmer or cooler climate on forest productivity are unknown, although higher temperatures will most likely increase productivity. To accommodate this variability and uncertainty, model simulations specified changes of ±5 % and ±15 % in forest productivity, as influenced by air temperature (Table 1).

2.6.2 Climate: Precipitation and Stream Flow

Along with expected long-term changes in air temperature, the IPCC estimates that future precipitation patterns will also change. Wetter or dryer conditions are expressed in MAGIC through changes in the estimates of stream flow. More/less precipitation will result in more/less water movement through the soil profile and resultant stream flow. Changes of ±4 % and ±10 % in stream flow were simulated to evaluate the effects of potential future changes in precipitation regimes on BC supply (Table 1).

3 Results

3.1 Base Scenario

Model results for pre-industrial, ambient, and future soil and stream chemistry under the Base Scenario are presented in Fig. 2. Soil exchangeable Ca and BS showed decreasing trends throughout the duration of the simulation from 1860 to 2100, while soil pH had a decreasing trend between 1860 and 2005 with little simulated change between 2005 and 2100. These results reflect, in addition to BC inputs via weathering and atmospheric deposition, the removal of BC in harvested trees and BC leaching in response to continued S deposition. The simulated sum of BC (SBC) concentration in stream water increased during the simulation from 1860 to 2005, followed by a decrease which continued to the year 2100. There was also an increase in stream sulfate (SO_4^{2-}) concentration from 1860 to 2005 remaining nearly constant to year 2100.

Ambient acid neutralizing capacity (ANC) of stream water was nearly 30 % lower than simulated ANC during the pre-industrial period (Fig. 2). This trend of simulated decreasing ANC continues to the year 2100, in large part due to decreased S adsorption on soils over time (Turner et al. 1990). As the S adsorption capacity of the soils becomes exhausted, SO_4^{2-} leaching is expected to increase, even under lower levels of atmospheric S deposition (Sullivan et al. 2011).

Each of the modeled watersheds, except one, showed a decrease in soil BC since pre-industrial times. Model results suggested that soil nutrient pool reductions will continue to occur in the future under the Base Scenario (Fig. 3). For each nutrient BC, the exchangeable cation pool is expected to continue to decline in the future, in some watersheds to more than a 50 % decrease compared with the simulated pre-industrial condition.

3.2 Alternative Future Scenarios

Departures from the year 2100 median (across all 65 modeled sites) Base Scenario results for stream ANC and SBC and for soil BS and exchangeable Ca are shown in Fig. 4 for each of the alternative future scenarios. The largest departure from the Base Scenario for stream ANC was for the simulation based on the Dep4 scenario (CAA Title IV [6 %] reduction in S deposition). The largest departures from the Base Scenario for stream SBC and soil BC supply were found for simulations that were based on the two most inclusive harvesting scenarios (all non-wilderness areas harvested and all areas including wilderness harvested). Stream SBC concentrations were also moderately sensitive to simulated changes in stream flow, and stream ANC was moderately sensitive to future reductions in S deposition.

Soil BS and exchangeable Ca were relatively insensitive to simulated changes in the productivity scenarios (which reflected long-term changes in temperature), stream flow, and the highest simulated harvest removal rates of 85 % and 100 %. However, the more extreme scenarios representing substantially decreased stream flow and harvest removal rate did suggest somewhat larger changes in soil chemistry in response to these perturbations.

The distribution of simulated percent reduction in upper B horizon soil exchangeable Ca from 1860 to 2100 is shown in Table 2 for each of the alternative future scenarios. The scenarios are ranked from lowest to highest according to median simulated reduction. Although only a small number of alternative future scenarios suggested that soil exchangeable Ca might increase appreciably in the future relative to current Base Scenario conditions (Fig. 4), each of the scenario projections indicated that median year 2100 soil exchangeable Ca will be at least 20 % less than pre-industrial values (Table 2, Fig. 5). Calcium loss is
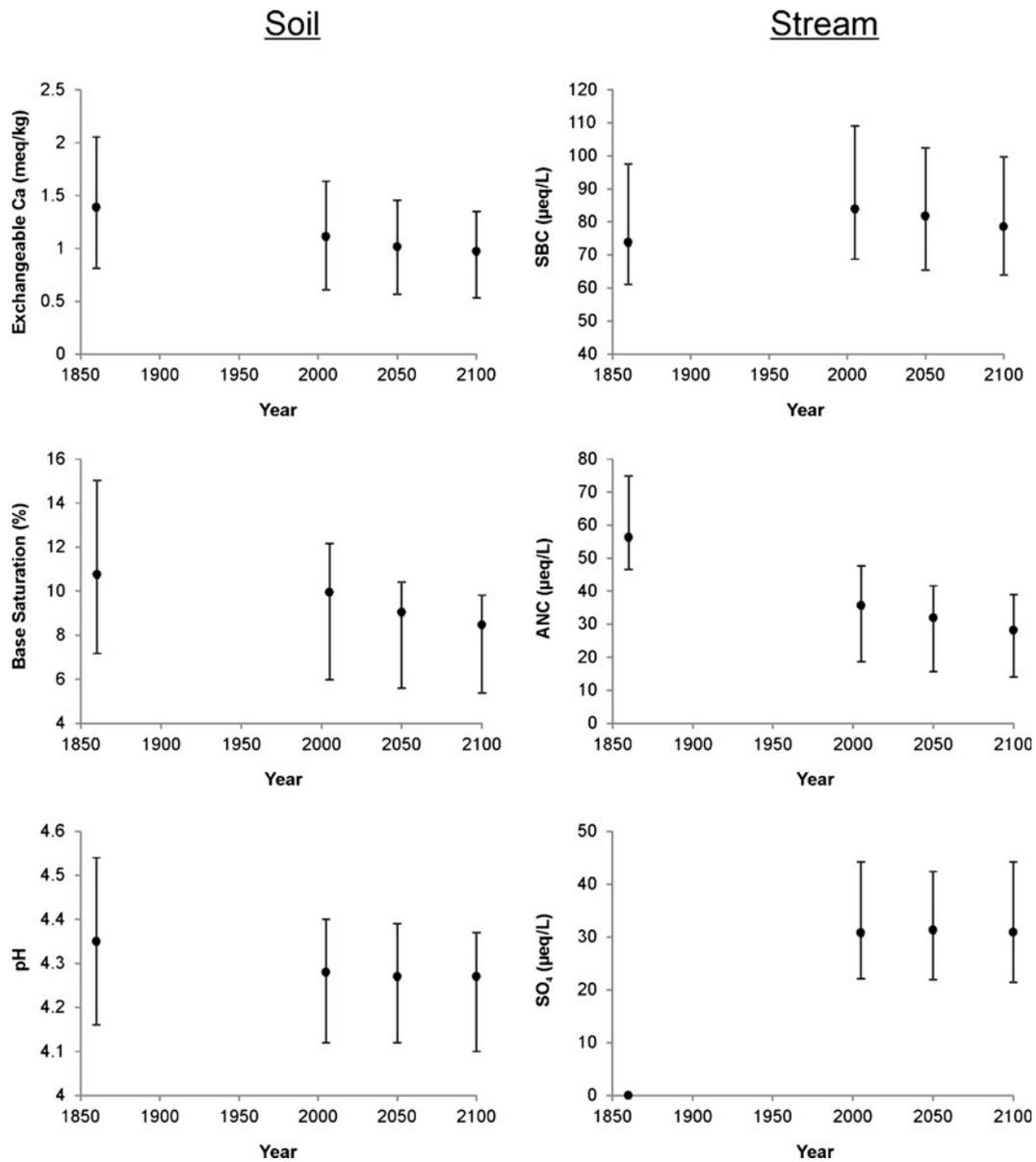
Fig. 2 MAGIC model simulation results for upper B horizon soil (*left panel*) and stream water (*right panel*) for selected years between 1860 and 2100 under the Base Scenario. Data are presented as median (*dot*) and quartile (*bars*) simulation results averaged across the 65 modeled sites

projected to be especially high (more than 50 %) for scenarios 19 and 20.

4 Discussion

The impacts of acidic deposition on soil exchangeable Ca and BS, and on stream ANC and SBC have reduced the ecosystem services provided by terrestrial and aquatic ecosystems on national forest lands in the SA Mountains (see report by Sullivan and McDonnell 2012 on the central Appalachian Mountain region). These include the presence and abundance of brook trout, aquatic species diversity, and likely a range of benefits associated with the presence, health, and growth of red spruce and sugar maple. In addition, historic timber harvests have also reduced soil BC pools, especially in the high elevation lands currently

Fig. 3 Percent of modeled watersheds among various classes showing a reduction in simulated pre-industrial upper B horizon soil exchangeable nutrient base cation concentration (Ca, Mg and K) under the Base Scenario. Nutrient losses are shown for two different time periods: 1860–2005 and 1860–2100. Values adjacent to the bars indicate the number of watersheds included in each respective class
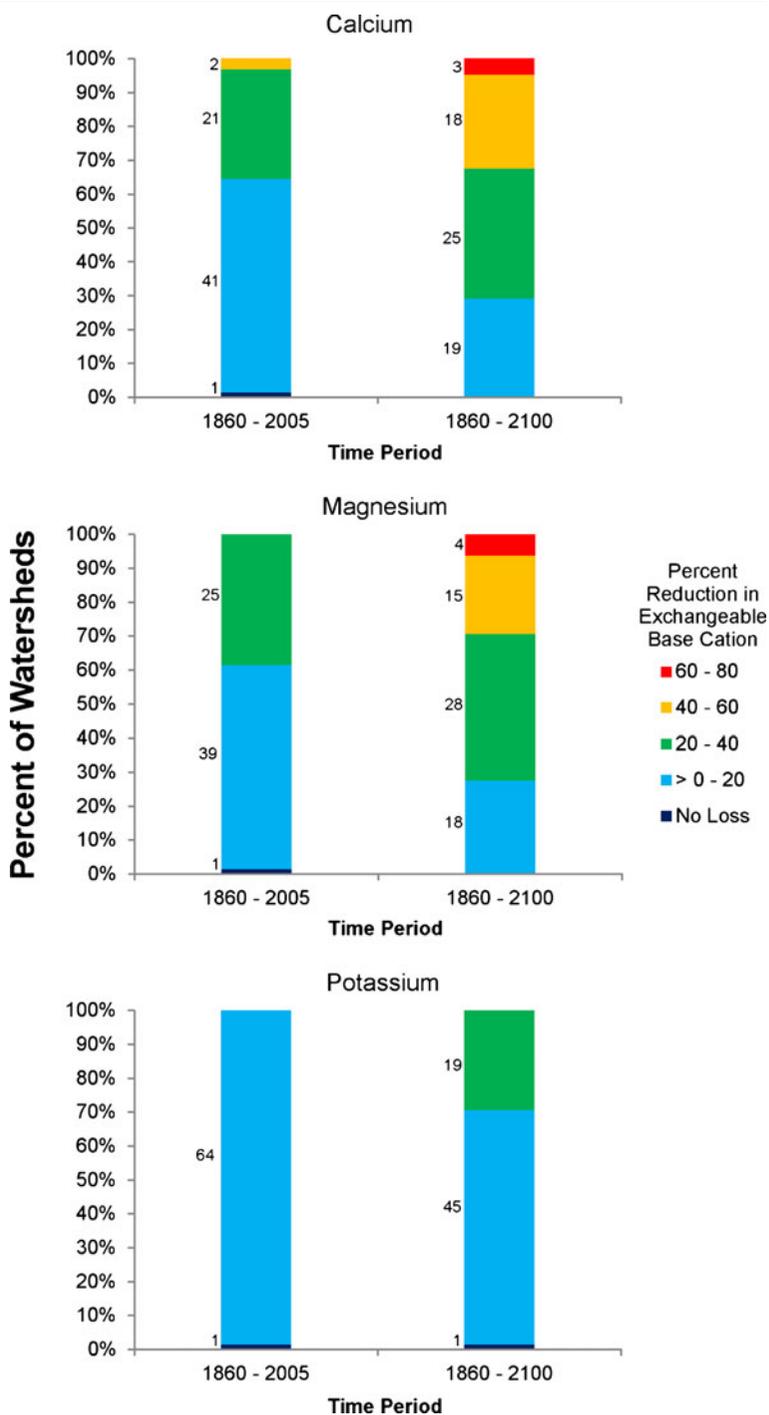
managed as wilderness or otherwise now considered to be unsuitable for harvesting. The simulated increase in stream SBC concentrations from the pre-industrial to the ambient (2005) time period was due to BC leaching from the soils in response to SO_4^{2-} and NO_3^- leaching

(Fig. 2). Furthermore, the simulated decrease in SBC leaching from ambient conditions to the year 2100, as reflected by decreasing SBC concentrations in stream water (Fig. 2), is a reflection of soil BC depletion, whereby SO_4^{2-} leaching will more commonly be charge
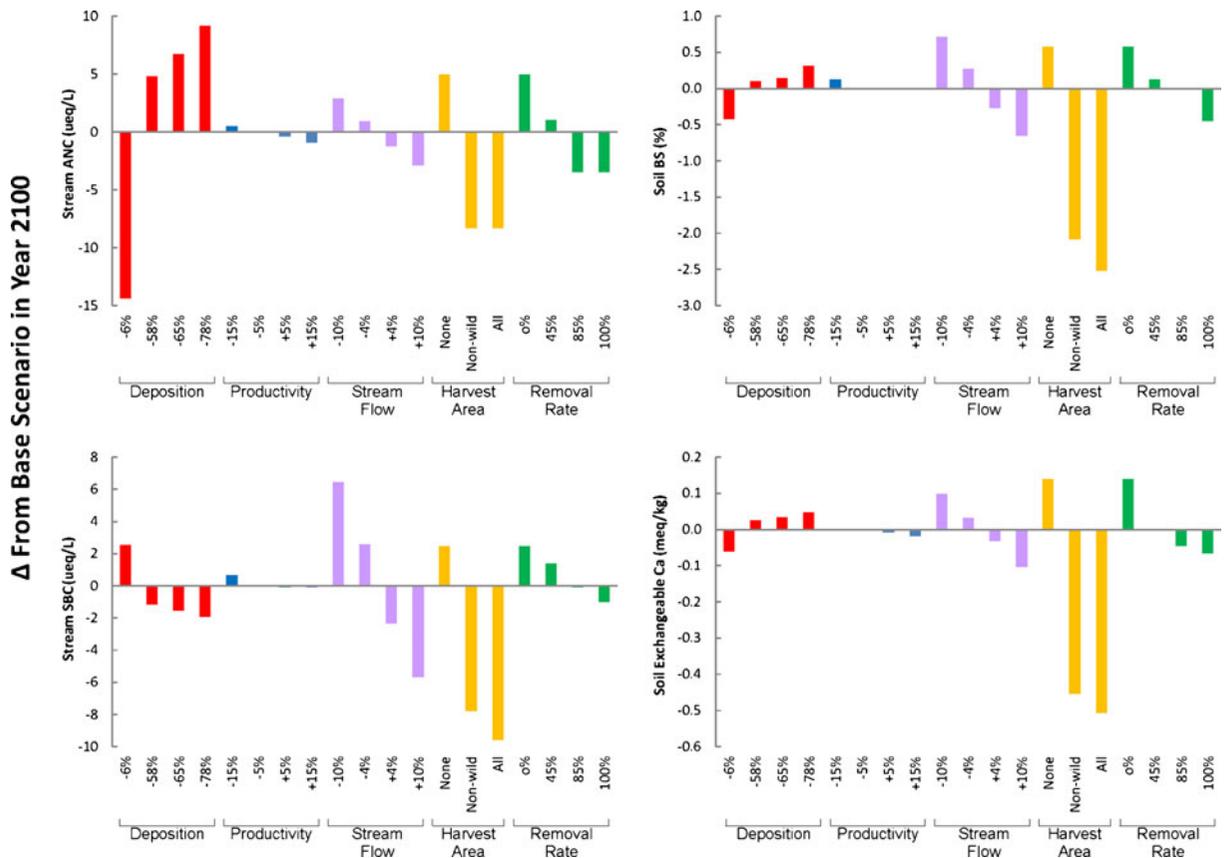
Fig. 4 Departure from Base Scenario results of model simulations for stream ANC and sum of base cations (*SBC*), and soil BS and exchangeable Ca in the year 2100 for each alternative future scenario. Scenarios are grouped according to type: Deposition (*red*), Productivity (*blue*), Stream flow (*purple*), Harvest Area (*orange*) and Removal Rate (*green*). Positive and negative values indicate an increase and decrease, respectively, in the parameter value relative to the Base Scenario

balanced by H^+ and Al^{n+} in the future rather than BC. This simulated deterioration of soil BC status began with the harvesting of timber in the early 1900s. The rate of soil BC loss was accelerated by S, and to a lesser extent N, deposition caused largely by the combustion of fossil fuels, reduced S adsorption on soil, and increased desorption of historically retained S.

For the soils considered in this study, substantial mass loss of soil BC has occurred since pre-industrial times (Figs. 2 and 6a). Under the Base Scenario, nearly the same magnitude of BC loss is expected to occur over the following 145 years (Fig. 6b), even under substantial additional future reductions in S deposition. These results represent BC losses in the mineral soil and are based on the soil depth and bulk density used in the MAGIC calibrations along with an assumption that modeled changes in exchangeable BC supply are consistent throughout mineral soil horizons. Median mineral soil BC loss was estimated

to be 53, 25, and 28 kg/ha from 1860 to 2005 for Ca, Mg, and K, respectively. These results suggest that the rate of BC deposition and BC weathering have not been sufficient to maintain pre-industrial mineral soil exchangeable BC pools. None of the future individual scenarios considered here are expected to completely recover these median watershed BC losses by the year 2100 and exchangeable Ca under all scenarios evaluated is predicted to remain at least 20 % reduced from the historical supply for the median watershed by the year 2100 (Fig. 5). Under the Base Scenario, the additional median loss of Ca, Mg and K from 2005 to 2150 is expected to be 41, 27 and 46 kg/ha, respectively.

The primary goal of this study was to evaluate potential drivers of soil BC supply on an individual basis. It is recognized that these drivers of BC supply can interact to compound or negate effects and such interactions are addressed by evaluating a combination

Table 2 Distribution among the 65 modeled watersheds of the simulated percent change in exchangeable Ca from 1860 to 2100 for each scenario, ranked by median change among the modeled watersheds

Rank	Scenario description			Change in exchangeable Ca (percentile)						
	ID	Perturbation	Value	Minimum	5th	25th	Median	75th	95th	Maximum
1	Mng1	Harvest Area	None	80.2	56.3	−4.0	−20.9	−41.0	−56.0	−73.0
2	Mng4	Removal	0 %	80.2	56.3	−4.0	−20.9	−41.0	−56.0	−73.0
3	Clm6	Stream flow	−10 %	19.9	2.0	−10.2	−22.0	−36.4	−50.9	−69.2
4	Dep3	Deposition	Scen. C (−78 %)	1.3	−10.0	−16.6	−24.5	−39.2	−53.4	−68.3
5	Mng5	Removal	45 %	18.7	−0.1	−12.2	−24.9	−41.3	−56.0	−73.0
6	Clm2	Productivity	−15 %	8.7	−8.6	−16.7	−25.2	−42.5	−56.5	−73.0
7	Dep2	Deposition	Scen. B (−65 %)	0.8	−10.6	−17.2	−26.0	−40.5	−54.4	−69.9
8	Clm5	Stream flow	−4 %	7.2	−6.4	−15.1	−26.0	−39.9	−54.7	−71.6
9	Dep1	Deposition	Scen. A (−58 %)	0.3	−10.7	−17.6	−27.0	−41.2	−55.0	−70.8
10	Clm1	Productivity	−5 %	2.6	−10.8	−18.0	−27.2	−43.0	−57.0	−73.0
11	Base	Base	Base	−0.5	−11.4	−18.2	−29.0	−43.1	−57.0	−73.0
12	Clm3	Productivity	+5 %	−3.6	−11.4	−19.3	−29.1	−43.6	−57.0	−73.0
13	Dep4	Deposition	Title IV (−6 %)	−3.1	−12.5	−21.1	−31.6	−47.2	−61.6	−77.5
14	Clm7	Stream flow	+4 %	−5.2	−15.5	−21.4	−31.6	−45.8	−59.1	−74.3
15	Clm4	Productivity	+15 %	−4.0	−11.4	−21.4	−33.7	−45.0	−57.0	−73.0
16	Clm8	Stream flow	+10 %	−6.9	−19.7	−26.3	−36.2	−49.3	−62.1	−76.0
17	Mng6	Removal	85 %	−4.0	−11.9	−21.4	−36.8	−47.5	−60.3	−73.0
18	Mng7	Removal	100 %	−4.1	−11.9	−23.1	−41.3	−52.1	−72.7	−80.8
19	Mng2	Harvest Area	Non-wild	−1.5	−13.5	−27.0	−55.2	−77.5	−100.0	−100.0
20	Mng3	Harvest Area	All	−1.5	−24.6	−44.0	−68.1	−83.8	−100.0	−100.0

of two scenarios (Dep3 and Mng1) to reflect the combined effect of the most aggressive management scenarios. The interaction effects were focused on these management scenarios because forest managers have no control over changes in future climate, and climate
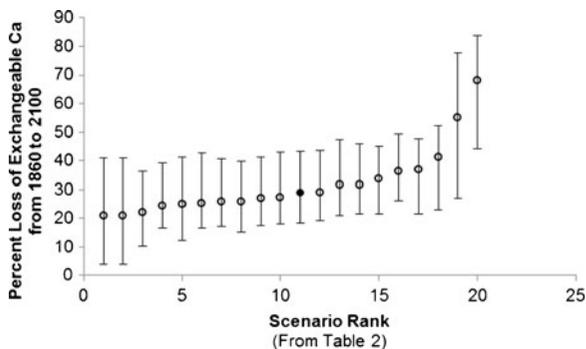

Fig. 5 Median (*circle*) and quartile (*bars*) percent loss of exchangeable Ca from 1860 to 2100 for each scenario. The scenarios are ranked from the lowest to highest median percent loss from *left* to *right*. The Base Scenario is shown as a *filled-in circle*. See Table 2 for description of scenarios

effects on BC supply were relatively small compared to potential changes reflected in the S deposition and forest management scenarios (Fig. 4). Even under a scenario of aggressive management (decreased S deposition by 78 % and no future harvest), soil BC supply was not simulated to recover to pre-industrial exchangeable Ca conditions. Although specific interactions between climate change and management scenarios were not modeled, modeled changes in soil and stream acid–base chemistry (Fig. 4) may approximately be additive. For example, the effect on exchangeable Ca of increasing the harvest removal rate to 100 % might be offset by a change in stream flow of −10 %.

In this study, MAGIC was used to evaluate a number of alternative future scenarios to evaluate extreme conditions, understanding that many of the scenarios are not likely to occur in the future. Proposed state and federal air regulations in the eastern United States will likely further reduce S deposition beyond the 6 % assumed to occur as a result of Title IV of the CAA amendments of 1990 (Dep4 scenario, Table 1). Emissions reductions are

Fig. 6 Distribution of **a** historical 1860–2005 and **b** future 2005–2150 base cation losses (kg/ha) for the 65 model watersheds under the Base Scenario. *Asterisks* and *open circles* indicate data points more than 1.5× and 3×, respectively, the interquartile distance
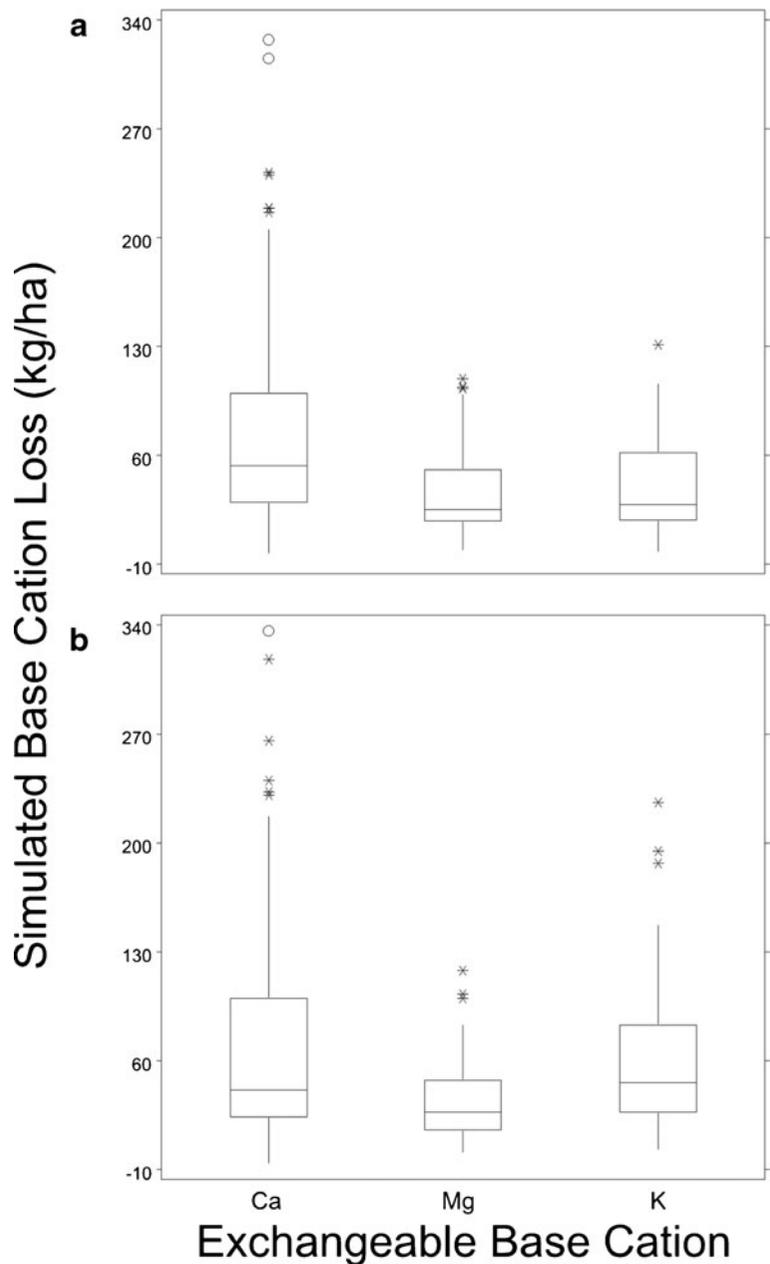
anticipated in the future as plans to improve air quality and visibility are implemented according to the national Regional Haze Rule. Proposed additional emissions reductions in the Clean Air Interstate Rule (CAIR) and the Cross-State Air Pollution Rule (CSAPR) have called for an additional approximately 42 % reduction in S deposition. Nevertheless, the model simulations suggest that stream ANC, and soil BS and exchangeable Ca would be expected to continue to decline. Additional S deposition reductions at or above 58 % will provide

additional soil and stream chemistry improvements relative to what is expected under the Base Scenario. Further reductions in S deposition may occur with either additional S emissions controls or with continued replacement of coal-fired power plants with natural gas, biomass, or other alternative energy sources for electricity generation in and upwind of the region.

Timber harvesting in wilderness and other lands classified as unsuitable for harvest was also evaluated, even though it is not expected that this would ever occur. This

extreme scenario was evaluated to ascertain the sensitivity of the model projections to harvesting level. Results show the potential for significant impacts of timber harvesting on the acid–base chemistry of streams and soils (Fig. 4). Land managers may decide to implement management strategies that maintain dead trees on unsuitable lands subsequent to large-scale blowdown, ice storm damage, or insect/disease outbreak, rather than removing bark and boles from the sites in commercial salvage operations. In wilderness areas, existing management policies dictate that there will be no timber harvesting or salvage operations even if there is widespread tree morality. Additional timber harvesting was shown to have the most impact on exchangeable Ca supply (Table 2). Since increased rates of timber harvest are not likely in this region, land managers should recognize that future BC supplies may be most strongly affected by changes in precipitation and subsequent soil water movement to streams (Fig. 4). However, these effects are projected to be relatively minor, with a ±10 % change in stream flow corresponding to approximately a ±0.7 % change in BS and a ±0.1 meq/kg change in exchangeable Ca.

Results of the individual model scenarios suggested that changes in existing forest harvest practices, climate, or additional reductions in S deposition are not expected to recover historic BC losses prior to the year 2100 (Table 2). Each of the scenarios also forecasted continued future BC losses relative to the ambient (year 2005) BC supply. However, complete cessation of tree harvesting was most effective at recovering soil Ca supply, indicating that forest management practices have the largest control on the future of SA forest health as it relates to soil BC status among the scenarios considered. Large (78 %) future reductions in S deposition are expected to result in increased BC supply relative to the Base Scenario. However, if these two aggressive management scenarios were to occur simultaneously the combined effect would remain insufficient to prevent further BC losses and recover historic losses (data not shown).

4.1 Base Cation Fertilization

Managers can also consider fertilization of watershed soils with BC to ameliorate the historic loss of soil nutrients, restore BS, and prevent future BC losses. For example, land managers may want to consider mitigating the impacts on nutrient base cation supply associated with future timber harvesting by fertilizing

the forests to replace BC lost with removal of the bark and boles from the watershed. However, it will be necessary to consider the feasibility of fertilizer application along with potential positive and negative effects of BC fertilization prior to implementation of such a management strategy.

Application of BC fertilizers has been used as a method for restoring exchangeable BC to base-depleted European and North American forest soils (e.g., Huettl 1989; Kreutzer 1995; Pabian and Brittingham 2007; Nohrstedt 2002; Cho et al. 2010; Côtè et al. 1993; Sharpe and Voorhees 2006; Moore and Ouimet 2010; Long et al. 2011). Nutrient base cations have been applied in various forms, including dolomite, wollastonite, and potash of sulfur. Application of BC fertilizer has generally been associated with significant positive effects on soil nutrient status as well as variety of terrestrial ecological metrics including snail and bird abundance, forb ground cover, and tree health (Huettl 1989; Pabian et al. 2012; Long et al. 1997; Wilmot et al. 1996; Halman et al. 2008).

Whole watershed BC fertilization is a potentially viable option for re-establishing pre-industrial BC pools and preventing further BC losses in the SA as well. The interquartile range of simulated BC loss from 1860 to 2150 among the modeled watersheds was 52–201 kg Ca/ha, 32–99 kg Mg/ha and 44–145 kg K/ha. Although some of the modeled watersheds were estimated to exhibit larger BC losses, successful BC fertilization at these rates would recover and prevent BC losses at approximately 75 % of the modeled sites.

A liming study was conducted in the Linville Gorge Wilderness (LGW) with an application rate of 247 kg Ca/ha and 129 kg Mg/ha as dolomitic lime on forest plots recently subjected to wildfire (Elliott et al. 2013). Average soil chemistry data 1–2 years after liming indicated that the moderately burned site with dolomite application showed 15 times more Ca in the upper (0–10 cm) mineral soil as compared with the reference site. The Ca and Mg fertilization rates used in the Elliott et al. (2013) study are similar to the estimated losses of these nutrients in the modeled watersheds of this study. However, the fertilization effect of wildfire could not be separated from the effect of the liming application in the LGW study.

Other studies have also shown positive effects of BC fertilization on base-depleted soils. Significant increases in soil BC pools were observed in organic soils after fertilization with 155, 33 and 255 kg/ha of Ca, Mg and K, respectively, in sugar maple stands located in southern

Quebec (Côtè et al. 1993). Calcium fertilization with wollastonite ($CaSiO_3$) was applied in an experimental watershed at Hubbard Brook Experimental Forest, New Hampshire (Cho et al. 2010). It was determined that 30.2 tons of wollastonite would be required to raise whole solum BS from 10 % to 19 % in the 11.8-ha watershed (~850 kg Ca/ha). The actual amount applied was 1,316 kg Ca/ha to account for potential losses and inefficient dissolution and mobility within the soil profile. Marked increases in exchangeable Ca in organic soils were observed following Ca fertilization and mobility within the soil profile. However, mineral soil exchangeable Ca was largely unaffected in the short term at the low to mid watershed elevations. In contrast, a doubling of upper mineral soil exchangeable Ca was observed in soils of a high-elevation red spruce forest 3 years after the Ca addition (Cho et al. 2010).

Fertilization experiments in a Norway spruce forest located in SW Sweden examined the effects on soil nutrient status of various forms and amounts of BC fertilizer application (Nohrstedt 2002). Addition of 1,135 kg/ha of Ca and 128 kg/ha of Mg, comprised of equal parts crushed calcite and dolomite, caused a 297 % increase in exchangeable Ca and Mg in organic soils. There were also 66 % and 15 % increases in exchangeable Ca+Mg in the top 5 cm and the 5–10 cm depth of mineral soil, respectively, 4 years after application. The author concluded that movement of Ca and Mg from the soil surface to deeper mineral soil horizons is a slow process that occurs over a period of multiple years. Potassium chloride applied at rates of both 79 and 158 kg K/ha did not result in any appreciable effect on exchangeable K in either organic or mineral soils 4 years after application. The reason for this result was not known, although it was postulated that it was due to the combined effects of K leaching and plant uptake (Nohrstedt 2002).

Potential drawbacks of BC fertilization may include increased nitrification and associated increased NO_3^- leaching, induced K (in the case of Ca and/or Mg application) or boron deficiency, mobilization of heavy metals, and enhanced fine root development in the surface soil horizons. The latter effect could contribute to increased risk of damage to trees by windthrow, frost, or drought (Huettl and Zoettl 1993; Kreutzer 1995), which may be important concerns under a changing future climate. It is not known whether any of these possible effects of BC addition are important in forests in the SA mountain region. Because forest liming entails ecological risks, a careful analysis concerning the need for liming should be conducted in any potential treatment area (Huettl and Zoettl 1993).

Consideration of the form(s) and dose(s) of BC fertilizer can optimize benefits and minimize detriments to forest ecosystems. Given the uncertainly in the movement of surface applied BC fertilizer into mineral soils, it is recommended to develop pilot studies to evaluate the efficacy of BC fertilization on mineral soil nutrient pools in SA forests prior to engaging in widespread fertilizer application in the SA region. Land managers and others need to be aware, however, that the model simulations suggest about 40 % of the sites in this study had ≤10 % BS in 1860 and therefore they should be cautious with BC fertilization so that the resulting base cation supplies will not be above the historical levels.

5 Conclusions

The relatively acid-sensitive watersheds of the SA region evaluated in this study were considered to be generally reflective of the surrounding national forest land area where forest management actions may be required in order to restore the loss of ecosystem services caused by continued elevated atmospheric S deposition. Soil BC pools in the study region are expected to remain significantly below pre-industrial conditions for more than 100 years into the future, regardless of changes in climate, S deposition, or timber harvest. Forest management actions such as BC fertilization will be required to fully recover BC supply to historical conditions in a time frame relevant to forest managers. Results presented here can be used as the basis for establishing BC fertilization rates in pilot studies to consider the effectiveness of fertilizer application for the recovery of soil BC supply in the SA region.

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