

Atmospheric Deposition Effects Modeling for Resource Management on Southern Appalachian National Forests

Final Report

Prepared for:
USDA Forest Service
Asheville, North Carolina

Prepared by:
E&S Environmental Chemistry, Inc.
Corvallis, OR

T.C. McDonnell¹
W.A. Jackson²
B.J. Cosby³
T.J. Sullivan¹

December 14, 2018 (Revised)

¹ E&S Environmental Chemistry, Inc., PO Box 609, Corvallis, OR

² USDA Forest Service, 160A Zillicoa St., Asheville, NC

³ Centre for Ecology and Hydrology, Environment Centre Wales, Bangor, Gwynedd, United Kingdom

ACKNOWLEDGMENTS

This research was supported by a contract between the USDA Forest Service and E&S Environmental Chemistry, Inc. We thank Paul Hessburg and Keith Reynolds for technical assistance and Nick Povak for assistance with developing the ANC threshold model. Jayne Charles and Deian Moore contributed to graphics design and document production.

Suggested Citation: McDonnell, T.C., W.A. Jackson, B.J. Cosby, and T.J. Sullivan. 2018. Atmospheric Deposition Effects Modeling for Resource Management on Southern Appalachian National Forests. Final Report prepared for USDA Forest Service – Asheville, NC. E&S Environmental Chemistry, Inc., Corvallis, OR.

Table of Contents

Acknowledgments	2
List of Figures.....	5
List of Tables	6
List of Abbreviations and Acronyms	7
1 Introduction.....	10
2 Methods	14
2.1 Model Site Selection	14
2.2 Site-Specific MAGIC Model Implementation	16
2.2.1 Model Description.....	16
2.2.2 Model Inputs	17
2.2.2.1 Stream and Soil Chemistry	17
2.2.2.2 Runoff.....	18
2.2.2.3 Nutrient Uptake	18
2.2.2.4 Temporal Sequences in Atmospheric Deposition.....	19
2.2.2.5 Calibration	20
2.2.3 Model Projections	21
2.2.4 Target Loads	23
2.3 Regional Modeling.....	23
2.3.1 Predicting ANC and BC _w	23
2.3.2 Steady-State Critical Loads.....	27
3 Modeling Output.....	30
3.1 MAGIC Modeled Streams	30
3.1.1 Scenarios	30
3.1.2 Target Loads	32
3.2 National Forest-Wide Streams	34
3.2.1 Regional ANC Model	34
3.2.2 Regional BC _w Model.....	36
3.2.3 Critical Loads of S Deposition and Exceedance	40
3.2.3.1 Aquatic.....	40
3.2.3.2 Terrestrial.....	40
4 Discussion and Management Implications	52
5 Conclusion	58
6 References Cited	61
Appendices.....	1
Appendix 1. Pre-Industrial Base Cation Cycling.....	2
Appendix 2. Candidate Predictor Variables for Regression Modeling.....	4
Appendix 3. Water Chemistry Site Locations (North/South)	7
Appendix 4. MAGIC Modeled Acid Neutralizing Capacity (ANC) Scenario Results.....	8
Appendix 5. MAGIC Modeled Base Saturation Scenario Results	22

Appendix 6.	Target Loads of Sulfur (S) Deposition	36
Appendix 7.	Continuous Regression Models for Predicting Acid Neutralizing Capacity (ANC).....	43
Appendix 8.	Continuous Regression Models for Predicting Base Cation Weathering (BC _w)	44

LIST OF FIGURES

Figure 1.	Location of MAGIC model sites (n = 177) and stream water chemistry sample sites (n = 2,225) within the EMDS study region.	15
Figure 2.	MAGIC calibration results for stream water sulfate (SO_4^{2-}), sum of base cations (SBC), calculated ANC (CALK); and soil base saturation (BS1).	22
Figure 3.	Trends in MAGIC modeled a) ANC, b) base saturation (BS), and c) stream sulfate from 1860 to 2170 among MAGIC sites (n = 177).	31
Figure 4.	Northern ANC model results for a) training data and b) test data showing predicted versus observed ANC ($\mu\text{eq/L}$; open circles) and 1:1 line (solid black line). RMSE is root mean squared error and MAE is mean absolute error.	35
Figure 5.	Southern ANC model results for a) training data and b) test data showing predicted versus observed ANC ($\mu\text{eq/L}$; open circles) and 1:1 line (solid black line). RMSE is root mean squared error and MAE is mean absolute error.	35
Figure 6.	Spatial variation in extrapolated acid neutralizing capacity (ANC) among the southern Appalachian national forests.	37
Figure 7.	Predicted versus observed (MAGIC modeled) base cation weathering (BC_w) for the regression models based on a) only landscape variables and b) landscape + water chemistry variables. The solid black line represents the 1:1 line. RMSE is root mean squared error and MAE is mean absolute error.	38
Figure 8.	Spatial variation in extrapolated base cation weathering (BC_w) among the southern Appalachian national forests.	39
Figure 9.	Spatial variation in aquatic critical loads of S deposition among the southern Appalachian national forests.	41
Figure 10.	Spatial variation in extrapolated stream nitrate (NO_3^-) concentration among the southern Appalachian national forests.	43
Figure 11a.	Spatial variation in aquatic S critical load exceedance among the southern Appalachian national forests with the effect of ambient NO_3^- leaching.	44
Figure 11b.	Spatial variation in aquatic S critical load exceedance among the southern Appalachian national forests without the effect of ambient NO_3^- leaching.	45
Figure 12.	Spatial variation in terrestrial critical loads of S deposition among the southern Appalachian national forests.	47
Figure 13.	Spatial variation in terrestrial S critical load exceedance among the southern Appalachian national forests without the effect of ambient NO_3^- leaching.	49
Figure 14.	Proposed pathway for inclusion of terrestrial critical loads (CLs) and temperature impacts to brook trout into the existing EMDS system for evaluating aquatic impacts from atmospheric S deposition.	51

LIST OF TABLES

Table 1.	Number of streams within various ANC classes according to MAGIC modeled pre-industrial (1860), ambient (2016), and future scenario (2100) ANC conditions.....	32
Table 2.	Number of catchments within various base saturation (BS; %) classes according to MAGIC modeled pre-industrial (1860), ambient (2016), and future scenario (2100) conditions.	32
Table 3.	Number of streams within various classes of target loads of sulfur (S) deposition to attain a critical ANC criterion of 30 and 50 $\mu\text{eq/L}$ for endpoint years 2060, 2100, and 2170.	33
Table 4.	Number of streams in exceedance, not in exceedance, or uncertain with respect to exceedance of S target loads for critical ANC criteria of 30 and 50 $\mu\text{eq/L}$ and endpoint years 2060, 2100, and 2170 based on estimates of year 2016 S deposition. Exceedance was considered uncertain if S deposition was within 10 $\text{meq/m}^2/\text{yr}$ of the critical load.	34
Table 5.	Area and percent of each national forest included within designated ambient stream water acid neutralizing capacity (ANC; $\mu\text{eq/L}$) classes based upon the continuous ANC regression model.	36
Table 6.	Area and percent of each national forest included within designated base cation weathering (BC_w ; $\text{meq/m}^2/\text{yr}$) classes.	38
Table 7.	Area and percent of each national forest included within designated aquatic critical load (CL; $\text{meq/m}^2/\text{yr}$) classes.	42
Table 8.	Area and percent of each national forest included within designated stream water nitrate (NO_3^- ; $\mu\text{eq/L}$) classes.....	42
Table 9.	Area and percent of each national forest included within designated aquatic critical load (CL) exceedance ($\text{meq/m}^2/\text{yr}$) classes for attaining stream water ANC = 50 $\mu\text{eq/L}$	46
Table 10.	Area and percent of each national forest included within designated aquatic critical load (CL) exceedance ($\text{meq/m}^2/\text{yr}$) classes considering the effect of nitrate (NO_3^-) leaching.	46
Table 11.	Area and percent of each national forest included within designated terrestrial critical load (CL; $\text{meq/m}^2/\text{yr}$) classes for attaining soil solution nutrient base cation to aluminum (Bc/Al) = 1 or 10 for the protection of coniferous and deciduous trees, respectively.	48
Table 12.	Area and percent of each national forest included within designated aquatic critical load (CL) exceedance ($\text{meq/m}^2/\text{yr}$) classes.	50

LIST OF ABBREVIATIONS AND ACRONYMS

Al	aluminum
Al _i	inorganic aluminum
ANC	acid neutralizing capacity
ANC _{crit}	specified critical ANC threshold (µeq/L)
ANC _{le,crit}	critical leaching of ANC based on a specified protective nutrient base cation to Al ratio in soil solution
ANC _{limit}	critical ANC stream flux based on a specified ANC concentration for protecting aquatic biota
ASTRAP	Advanced Statistical Trajectory Regional Air Pollution
BC	base cation sum
Bc	nutrient base cation sum
(Bc/Al) _{crit}	specified critical soil solution Bc/Al for protecting terrestrial vegetation
BC _{dep}	total deposition of base cations to the watershed
BC _{stream}	stream water base cation flux
Bc _{up}	watershed average nutrient base cation uptake
BC _w	base cation weathering
Bc _w	nutrient base cation weathering
BC _{w,FB}	base cation flux balance
BS	base saturation
C	carbon
Ca ²⁺	calcium
CALK	calculated ANC
CEC	cation exchange capacity
CL	critical load
Cl _{dep}	total chloride deposition
CO ₂	carbon dioxide
EMDS	Ecosystem Management Decision Support (system)
EPA	Environmental Protection Agency
F ⁻	fluoride

FIA	Forest Inventory Analysis
FISH	Fish in Sensitive Habitats (project)
GAP	GAP Analysis Program
H ⁺	hydrogen ion
K	potassium
K _{gibb}	gibbsite equilibrium constant
ILTER	Long Term Ecological Research
MAE	mean absolute error
MAGIC	Model of Acidification of Groundwater in Catchments
μeq/L	microequivalents per liter
Mg	magnesium
N	nitrogen
NADP	National Atmospheric Deposition Program
NAPAP	National Acid Precipitation Assessment Program
NF	national forest
NH ₄ ⁺	ammonium
NHDPlus	National Hydrology Dataset Plus
N _{leach}	estimate of N leaching
NO ₃ ⁻	nitrate
NP	National Park
NRSA	National Rivers and Streams Assessment
Q	watershed runoff
RedN	reduced N
RH	regional haze
RMSE	root mean squared error
S	sulfur
SAMI	Southern Appalachian Mountains Initiative
SBC	sum of base cations
S _{dep}	S deposition rate used for determining CL exceedance
SMB	Simple Mass Balance (model)
SO ₄ ²⁻	sulfate
SSWC	Steady State Water Chemistry (model)

TDEP	Total Deposition
TL	target load
USFS	USDA Forest Service
USGS	U.S. Geological Survey
VIF	variance inflation factor
VTSSS	Virginia Trout Stream Sensitivity Study
WSA	Wadeable Streams Assessment

1 INTRODUCTION

Atmospheric sulfur (S) deposition, originating largely from coal-fired electrical power generation and also other industrial air pollution sources, has caused soil, soil water, and streamwater acidification across broad areas of the southeastern United States (U.S. EPA 2008). Such acidification has been associated with enhanced leaching of sulfate (SO_4^{2-}) to drainage waters, calcium (Ca^{2+}) and other base cation (BC) depletion from soil, reduced pH and acid neutralizing capacity (ANC) of surface waters, and increased mobilization of potentially toxic inorganic aluminum (Al_i) to soil water and streams (Sullivan 2017). Biological effects in streams have included toxicity to fish and aquatic invertebrates (Cosby et al. 2006, U.S. EPA 2009).

Throughout the eastern United States, S is the primary determinant of precipitation acidity and SO_4^{2-} is the dominant acid anion associated with streams throughout most of the southern Appalachian Mountains region (Sullivan et al. 2004). Although a substantial proportion of atmospherically deposited S is retained in watershed soils in this region, SO_4^{2-} concentrations in many mountain streams have increased in response to atmospheric deposition (Andrew et al. 2013).

Ecosystem sensitivity to acidification and the potential effects of atmospheric S deposition on surface water quality have been well studied in this region, particularly within the National Acid Precipitation Assessment Program (NAPAP; 1991), the Fish in Sensitive Habitats (FISH) project (Bulger et al. 1999), the Southern Appalachian Mountains Initiative (SAMI; 2007, Sullivan et al. 2004), the Appalachian Trail Assessment (Lawrence et al. 2015), several studies for the USDA Forest Service (USFS; McDonnell et al. 2012, McDonnell et al. 2013, McDonnell et al. 2014, Povak et al. 2013, Povak et al. 2014, Sullivan et al. 2011a, Sullivan et al. 2011c), and the assessment by Sullivan (2017) of air pollution effects in the national parks. Stream water ANC is one measure that reflects the ability of a watershed to neutralize acidic

inputs. As the rate of acidic deposition increases, ANC often decreases in proportion to the natural re-supply of BCs from the soil. Reduced ANC is associated with decreased pH and increased Al_i in streams. Large increases in hydrogen ion (H^+) and Al_i concentration can be directly toxic to fish, including brook trout (*Salvelinus fontinalis*; Baldigo et al. 2007, Baldigo et al. 2018, Bulger et al. 1999), which is the principal game fish native to the high-elevation areas. Various ANC thresholds are associated with different biological effects (U.S. EPA 2009). In the southern Appalachians and mountainous areas of the northeastern United States, moderate effects on macroinvertebrate and fish species richness are associated with ANC concentrations occurring between ~50 and 100 $\mu\text{eq/L}$ (Cosby et al. 2006, Sullivan et al. 2006). More substantial effects have been observed at ANC concentrations <50 $\mu\text{eq/L}$ (Bulger et al. 1999, Cosby et al. 2006, Sullivan et al. 2006, U.S. EPA 2009).

Federal land managers are concerned about the current and future health of terrestrial and aquatic resources within the southern Appalachian Mountains. Soils in some watersheds in this region have developed from the slow weathering of parent rock material which can be inherently low in base cations. Adequate amounts of available Ca, magnesium (Mg), and potassium (K) are essential to maintain healthy terrestrial vegetation and aquatic acid-base chemistry. Prior to the industrial revolution beginning in approximately 1860, soil base cation reserves were relatively constant (**Appendix 1**). Soil acidification resulting from elevated acidic deposition since 1860 has depleted soil base cation resources, lowered soil pH, and caused soil aluminum to mobilize into solution. Aluminum in soil solution can be toxic to the roots of some plants, and this effect is exacerbated under conditions of low soil exchangeable Ca. Tipping points are less clear for soil solution chemical indicators and associated impacts on trees and other vegetation. However, the effects of nutrient base cations (Bc; $\text{Ca} + \text{Mg} + \text{K}$) to Al below 1.0 in soil solution has been

used to indicate an increased likelihood of adverse terrestrial impacts to forest trees (Cronan and Grigal 1995).

Some wildernesses in the national forests and the two national parks in this region are designated as Class I and they receive special protection against adverse impacts from new sources of air pollution under the Clean Air Act; however, S, and to a lesser extent N, deposition has declined throughout the eastern United States since about the early 1980s, and further decreases are possible (Sullivan et al. 2018). Soil and drainage water acidification developed in this region over a period of many decades in response to high levels of atmospheric S deposition. Many streams in southern Appalachian Mountain National Forests, Great Smoky Mountains and Shenandoah national parks show signs of acidification (McDonnell et al. 2014, Sullivan 2017). Better information is now needed to accurately assess watershed responses that might be anticipated.

Resource managers in the USFS are confronted with questions regarding how to manage natural resources impacted by acidic deposition. To inform the resource managers regarding possible air pollutant impacts, it is important to 1) identify what are the thresholds of concern where impacts to natural resources may be unacceptable, 2) describe the linkages between water and soil chemistry and biological impacts, and 3) locate areas of concern across the landscape for possible impacts to natural resources.

One approach to addressing these issues for each National Forest in Southern Appalachia is to construct model estimates of regional base cation (BC; $\text{Ca}+\text{Mg}+\text{K}+\text{Na}$) weathering (BC_w). These BC_w data can be used to model surface water acid-base chemistry and critical loads (CLs). The CL for S acidification is the level of sustained atmospheric S deposition to a given watershed or forest below which harmful effects to sensitive ecosystems are unlikely according

to current scientific understanding (Nilsson and Grennfelt 1988). The CL is typically calculated as a steady state value, using models such as the Steady State Water Chemistry model (SSWC; Henriksen and Posch 2001) for aquatic systems and the Simple Mass Balance model (SMB; Posch et al. 2001) for terrestrial systems. Dynamic process-based models such as the Model of Acidification of Groundwater in Catchments (MAGIC; Cosby et al. 1985a, b) can be used to determine the target load (TL), a level of deposition that effectively protects the sensitive receptor under consideration at a designated time (i.e., streamwater ANC = 50 $\mu\text{eq/L}$ by the year 2100). Dynamic models such as MAGIC can also be used to reconstruct historical, and simulate future, soil and stream water acid-base chemistry under various scenarios of atmospheric S deposition and to estimate the base cation weathering rate, which is arguably the most important variable in the CL and TL calculations (Li and McNulty 2007).

An Ecosystem Management Decision Support (EMDS) system has previously been developed to evaluate stream ANC and CLs related to aquatic acidification throughout the southern Appalachian Mountains (McDonnell et al. 2014, Reynolds et al. 2012). This original EMDS system was developed to inform resource managers and policy makers of landscape scale sensitivity of stream systems to acidic atmospheric deposition. The research reported here builds on this earlier effort. A primary objective of this new work was to leverage recently collected soil and stream chemistry data to update the existing EMDS system. In addition, terrestrial CLs were developed and incorporated into the EMDS database to allow for evaluating terrestrial impacts of soil acidification caused by S deposition. The EMDS application is intended for use by federal, state, and other land management agencies and organizations to evaluate the current status of aquatic and terrestrial ecosystems they manage, and the potential for biological resource

recovery in response to future acidic deposition strategies in this highly acid-sensitive and impacted region.

2 METHODS

2.1 Model Site Selection

Availability of soil and stream chemistry data determined the locations within the EMDS region that could be used for conducting regional statistical ANC and BC_w modeling in this study and also for dynamic process-based simulation and TL modeling with the MAGIC model. Stream water quality data were aggregated for this study from several USFS and EPA databases, including:

- Seven national forests within USFS Region 8
- Monongahela NF within USFS Region 9
- Appalachian Trail Megatransect project
- EPA Wadeable Streams Assessment (WSA)
- EPA National Rivers and Streams Assessment (NRSA)
- Coweeta Hydrologic Laboratory
- Virginia Trout Stream Sensitivity Study (VTSSS)
- Great Smoky Mountains NP

After quality assurance evaluation, a total of 2,225 unique water chemistry sites were aggregated for use in developing statistical models for estimating spring season (February – June) ANC throughout the EMDS region (**Figure 1**). Measured soil chemistry data were available for a subset of the water chemistry sites ($n = 177$). This subset was used for site-specific calibration of the MAGIC model (Cosby et al. 1985b, Cosby et al. 2001), from which BC_w estimates were extracted and used for developing a statistical model for predicting BC_w throughout the EMDS region. The MAGIC model was also used for scenario and TL modeling at these 177 sites.

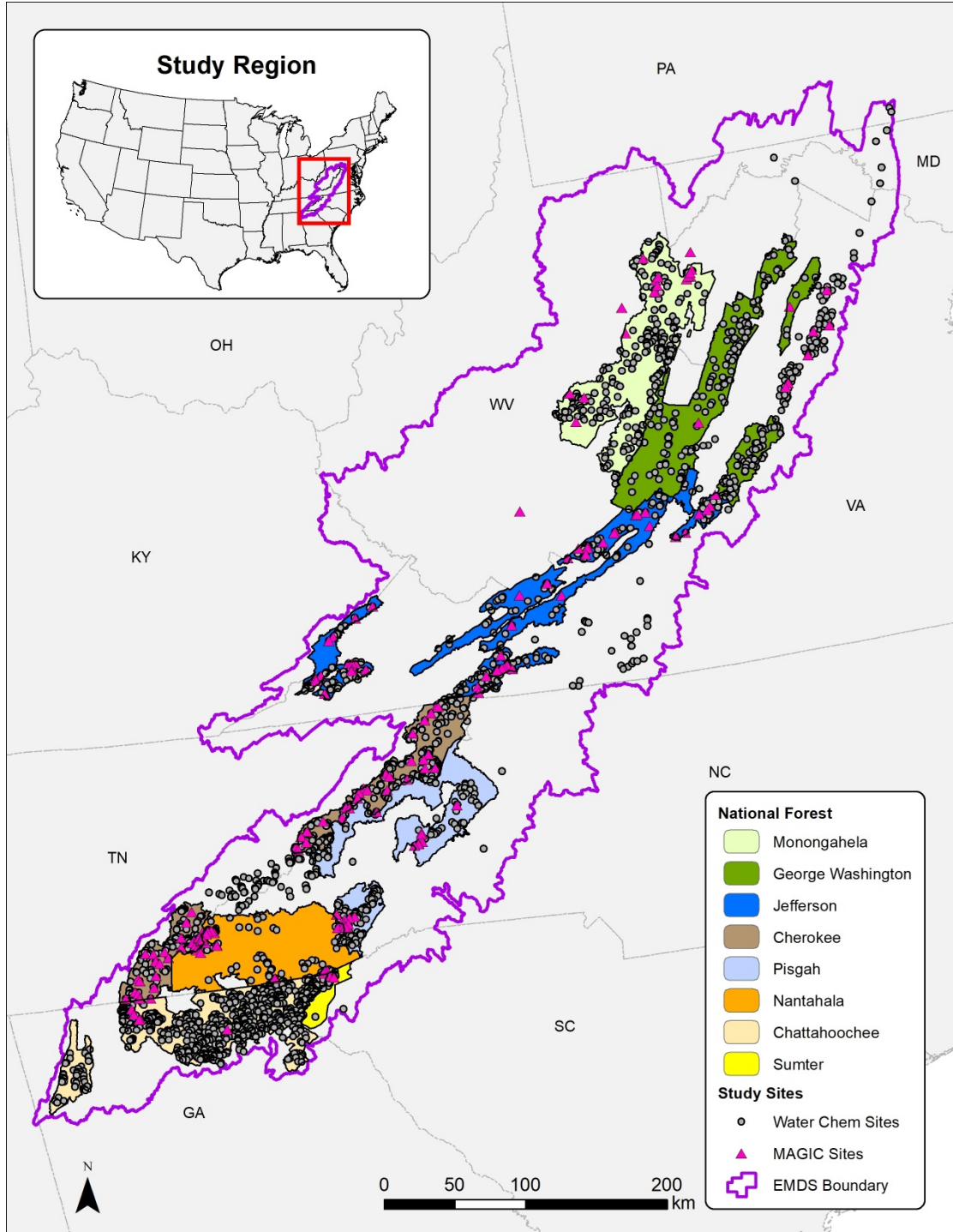


Figure 1. Location of MAGIC model sites ($n = 177$) and stream water chemistry sample sites ($n = 2,225$) within the EMDS study region.

2.2 Site-Specific MAGIC Model Implementation

2.2.1 Model Description

The MAGIC model was used for projecting future soil and stream chemistry under differing emissions and deposition levels and developing TLs of atmospheric N and S deposition. MAGIC is a lumped-parameter model of intermediate complexity, developed to predict the long-term effects of acidic deposition on soil and surface water chemistry (Cosby et al. 1985a, b). It simulates monthly and annual average concentrations of major ions in drainage waters. MAGIC consists of 1) a section in which the concentrations of major ions are assumed to be governed by simultaneous reactions involving SO_4^{2-} adsorption, cation exchange, dissolution-precipitation-speciation of Al and dissolution-speciation of inorganic C; and 2) a mass balance section in which the flux of major ions to and from the soil is assumed to be controlled by atmospheric inputs, chemical weathering, net uptake and loss in biomass, and loss to runoff. Central to MAGIC calculations is the size of the pool of exchangeable base cations on the soil. As the fluxes to and from this pool change over time in response to changes in atmospheric deposition, the chemical equilibria between soil and soil solution shift to give changes in surface water chemistry. The degree and rate of change of surface water acidity thus depend both on flux factors and the inherent characteristics of the affected soils.

Cation exchange is modeled using equilibrium (Gaines-Thomas) equations with selectivity coefficients for each base cation and Al. Sulfate adsorption is represented by a Langmuir isotherm. The only sources of S to the soils are assumed to be atmospheric deposition and, in some cases, underlying geology. Aluminum dissolution and precipitation are assumed to be controlled by equilibrium with a solid phase of $\text{Al}(\text{OH})_3$. Aluminum speciation is calculated by considering hydrolysis reactions as well as complexation with SO_4^{2-} and F^- . Effects of carbon dioxide (CO_2) on pH and on the speciation of inorganic C are computed from equilibrium

equations. Organic acids are represented in the model as tri-protic analogues. First-order rates are used for biological retention (uptake) of nitrate (NO_3^-) and ammonium (NH_4^+) in the soils and streams. The rate constants are typically not varied during the simulation period. Weathering rates for base cations are assumed to be constant.

Given a description of the historical deposition at a site, the model equations are solved numerically to give long-term reconstructions of soil and surface water chemistry. For complete details of the model see Cosby et al. (1985a, b, 2001, 1990). MAGIC has been used to reconstruct the history of acidification and to simulate the future trends on a regional basis and in a large number of individual watersheds in both North America and Europe (e.g., Cosby et al. 1996, Cosby et al. 1989, Cosby et al. 1990, Hornberger et al. 1989, Jenkins et al. 1990a, Jenkins et al. 1990b, Jenkins et al. 1990c, Norton et al. 1992, Sullivan and Cosby 1998, Sullivan et al. 2011a, Sullivan et al. 2011c, Sullivan et al. 2004, Wright et al. 1990, Wright et al. 1994).

2.2.2 *Model Inputs*

This section describes how input data for the MAGIC model were generated. Each of the input parameter values was calculated as a watershed average or was assumed to be representative of the entire watershed.

2.2.2.1 *Stream and Soil Chemistry*

Paired stream and watershed soil chemistry data necessary for model calibration were available for 177 sites. Stream data were collected and compiled from the above listed data sources and the most recent spring surface water sample was used as the basis for MAGIC calibration. Soil chemistry data were obtained from USFS Region 8, Lawrence et al. (2015), Coweeta Hydrologic Laboratory staff, and other databases (2011a, Sullivan et al. 2011c). For all

sites, MAGIC was parameterized with average soil chemistry data from the upper 10 cm of mineral (A/B) soil with data typically averaged across three soil cores at a given site location. Soil chemistry of the lower B horizon (e.g. 10 cm – 50 cm) was also used where available.

2.2.2.2 Runoff

Long-term (1971 – 2000) estimates of average annual runoff for each modeled watershed were derived from a water balance model (McCabe and Wolock 2011). Annual average watershed runoff (m/yr), defined as the difference between precipitation and evapotranspiration, was used to represent watershed runoff at all sites.

2.2.2.3 Nutrient Uptake

Forest nutrient uptake fluxes of N and the three nutrient base cations (Ca^{2+} , Mg^{2+} , K^{+} ; Bc_{up}) were estimated from literature values summarized for the USFS Forest Inventory Analysis (FIA) project by McNulty et al. (2007). To estimate nutrient removal in biomass from the watershed, estimates of annualized tree growth rate were used under the assumption that 65% of the bark and bole tree volume is removed from the site during harvest. These uptake terms reflect uptake into woody materials that are removed from the watershed through timber harvest. Uptake into vegetation that subsequently dies on site represents within-watershed recycling; this is not a net watershed loss. Lands identified as designated wilderness and other protected areas were classified as “no harvest”; nutrient uptake was set to zero in such areas. These included areas identified in the Protected Areas Database (v1.4) provided by USGS (<http://gapanalysis.usgs.gov/padus/>), corresponding to GAP Analysis Program (GAP) codes 1 and 2 (Scott et al. 1993). Nutrient uptake was also set to zero for other areas considered to be unsuitable or unavailable for harvesting.

2.2.2.4 Temporal Sequences in Atmospheric Deposition

Total deposition sequences for S and N from 2000 through 2015 were developed from the sum of wet (Grimm and Lynch 1997, Sullivan et al. 2002b), dry (TDEP; Schwede and Lear 2014), and occult (Shannon 1998, Sullivan et al. 2002b) deposition. Deposition sequences for S and N from 1860 to 1990 were developed based on emissions inventories and Advanced Statistical Trajectory Regional Air Pollution (ASTRAP) modeling (Sullivan et al. 2011a, Sullivan et al. 2004) applied to the Coweeta Hydrologic Laboratory location.

The sequences for the two time periods (1860-1990 and 2000-2015) were normalized and merged to produce scaled sequences having scale factors of 1 in the year 2016. Scale factors in other years express the relative magnitude of S and N deposition in that year compared to 2016. The relative deposition values for any site and year can be converted to absolute deposition values knowing the absolute deposition of S and N at a site in the deposition reference year 2016. The dry/wet ratios for all ions were assumed to be constant through time.

A stepwise procedure was used to calibrate stream SO_4^{2-} concentrations for the model simulations. First, a regression equation was developed to obtain site specific calibrated maximum SO_4^{2-} adsorption (Emx) values across all sites using *a priori* estimated S deposition. Second, calibrated Emx values for each site were used to re-calibrate stream SO_4^{2-} by adjusting *a priori* deposition of SO_4^{2-} to reflect local effects on S deposition. *A priori* deposition of NO_3^- and NH_4^+ were adjusted to maintain equivalent ratios of N to S.

Wet BC and Cl deposition data were obtained from J. Grimm (personal communication) and derived from National Atmospheric Deposition Program (NADP) monitoring. Total BC deposition was calculated based on dry-to-wet ratios included in Baker et al. (1991). *A priori* total deposition of Cl at each site was adjusted to match observed stream Cl concentrations. Adjustments to BC deposition were made to match the charge derived from the adjusted Cl

deposition. The BC and Cl deposition levels were assumed to be constant for all simulation years.

2.2.2.5 Calibration

The aggregated nature of the MAGIC model requires calibration to observed data from a system before examining potential system response. Calibration is achieved by setting the values of certain parameters within the model that can be directly measured or observed in the system of interest (called fixed parameters). The model is then run (using observed and/or assumed atmospheric and hydrologic inputs) and the outputs (stream water and soil chemical variables, called criterion variables) are compared to observed values of these variables. 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 adjusting the optimized parameters, the simulated-minus-observed values of the criterion variables usually converge to zero within some specified tolerance. The model is then considered calibrated.

Estimates of the fixed parameters, the deposition inputs, and the target variable values to which the model is calibrated all contain uncertainties. A “fuzzy optimization” procedure was used to provide explicit estimates of the effects of these uncertainties. The procedure consists of developing multiple calibrations at each site using random values of the fixed parameters. These are drawn from a range of potential fixed parameter values, representing uncertainty, and random values of Reference Year deposition drawn from a range of possible total deposition estimates, representing uncertainty in these inputs. The final convergence of the calibration is determined when the simulated values of the criterion variables are within a specified acceptable window around the nominal observed value. This acceptable window represents uncertainty in the target variable values used to calibrate the site.

Each of the multiple calibrations at a site began with (1) a random selection of values of fixed parameters and deposition, and (2) a random selection of the starting values of the adjustable parameters. The adjustable parameters were then optimized using an algorithm to minimize errors between simulated and observed criterion variables. Calibration success was judged when all criterion values simultaneously were within their specified acceptable windows. This procedure was repeated ten times for each site. For this project, the acceptable windows for base cation concentrations in streams were specified as $\pm 2 \mu\text{eq/L}$ around the observed values. Acceptable windows for soil exchangeable base cations were taken as $\pm 20\%$ around the observed values. Fixed parameter uncertainty in soil depth, bulk density, cation exchange capacity (CEC), stream discharge, and stream area of each ion were assumed to be $\pm 10\%$ of the estimated values. Reference year simulated vs. observed values for soil and stream variables are given in **Figure 2**.

2.2.3 Model Projections

Scenario results corresponding to simulated changes in future S and N deposition were developed using the MAGIC model. The scenarios considered in this project included reductions in S and N deposition described as:

Scenario 1 (Base Case)

- Constant total N and S deposition until 2170 (wet + dry + occult; 2013-2015 average)

Scenario 2 (Regional Haze; RH)

- 90% reduction in total (wet + dry + occult; 2013-2015 average) S deposition implemented by year 2060 then held constant until 2170
- 75% reduction in total (wet + dry + occult; 2013-2015 average) oxidized-N deposition implemented by year 2060 then held constant until 2170
- Constant total (wet + dry + occult; 2013-2015 average) reduced-N deposition until 2170

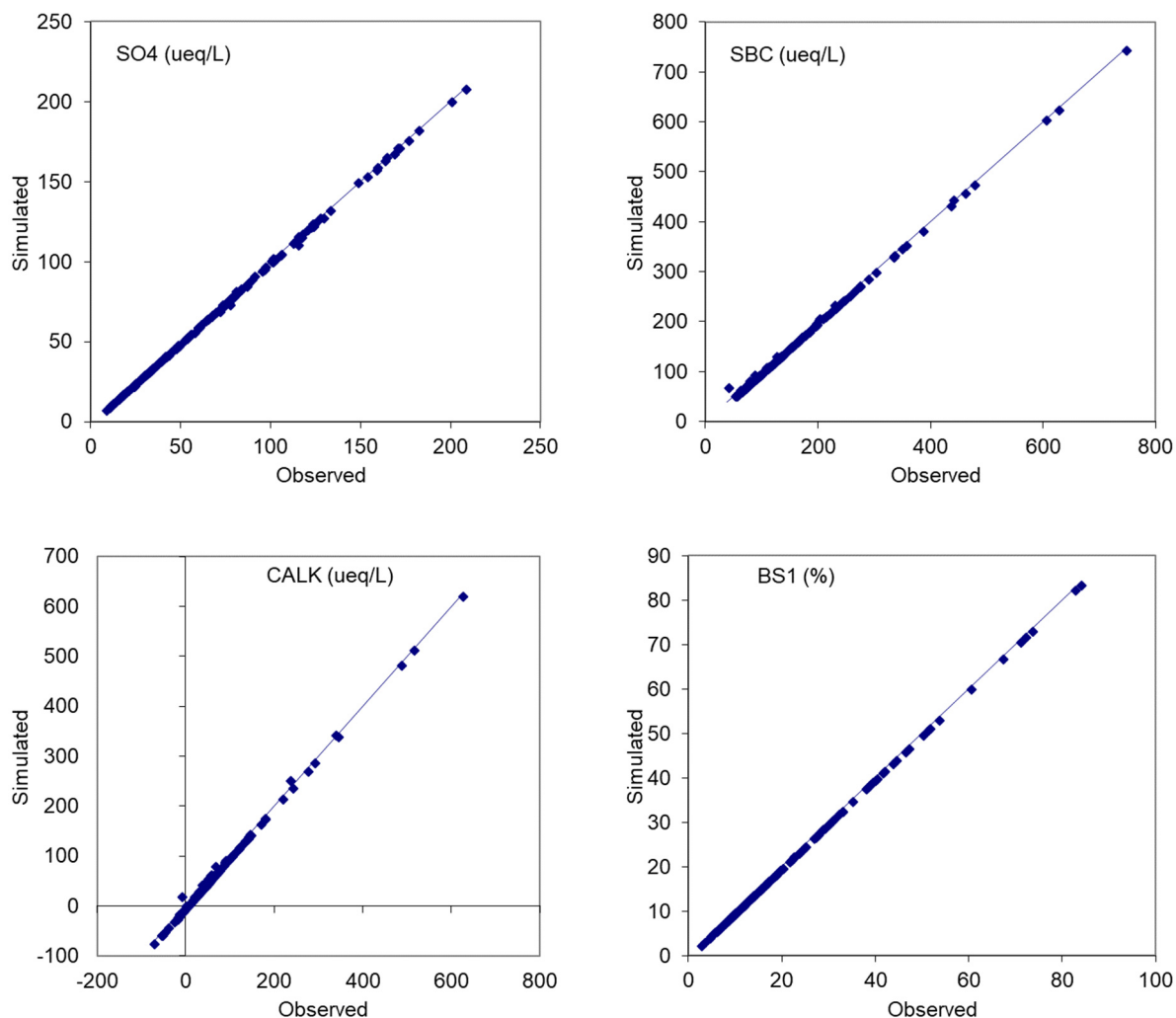


Figure 2. MAGIC calibration results for stream water sulfate (SO_4^{2-}), sum of base cations (SBC), calculated ANC (CALK); and soil base saturation (BS1).

Scenario 3 (Regional Haze and increase Reduced-N; RH+RedN)

- 90% reduction in total (wet + dry + occult; 2013-2015 average) S deposition implemented by year 2060 then held constant until 2170
- 75% reduction in total (wet + dry + occult; 2013-2015 average) oxidized-N deposition implemented by year 2060 then held constant until 2170
- 10% increase in total (wet + dry + occult; 2013-2015 average) reduced-N deposition held constant until 2170

2.2.4 Target Loads

The TL process implemented for this project selected stream water as the sensitive receptor and ANC as the chemical indicator. A number of critical criteria values of ANC have been used as the basis for CL calculations, the most common of which have been 0, 20, 50, and 100 $\mu\text{eq/L}$ (cf., Posch et al. 2001, U.S. EPA 2009). The first two levels approximately correspond in the Appalachian Mountains region to chronic and episodic effects on brook trout, respectively (Bulger et al. 1999). An ANC threshold of 50 to 100 $\mu\text{eq/L}$ is thought to be protective of general ecological health (cf., Cosby et al. 2006, U.S. EPA 2009). For this project, a set of eight ANC endpoint criterion was used to develop TLs with MAGIC: pre-industrial (year 1860) ANC, pre-industrial (year 1860) ANC minus 10 $\mu\text{eq/L}$, and ANC = 30, 40, 50, 60, 80, 100 $\mu\text{eq/L}$. The focus here is on the fixed endpoints 30 and 50 $\mu\text{eq/L}$. Target loads for each of these critical ANC values were evaluated for endpoint years 2060, 2100, and 2170. Target loads were generated for total S deposition, with total N deposition constant at 2017 values and N retention constant at 2017 values; and total N deposition, with total S deposition constant at 2017 values and N retention constant at 2017 values.

2.3 Regional Modeling

2.3.1 Predicting ANC and BC_w

A set of landscape predictor variables representing aspects of weather, atmospheric S deposition, forest type, soil conditions, lithology, location, and geomorphology was prepared for developing statistical regression models to predict ANC and BC_w throughout the region (**Appendix 2**). This set of predictors was selected based on known or expected landscape level influences on soil and stream acid-base status for the region (cf., Sullivan et al. 2002a, Sullivan et al. 2002b). To incorporate upslope conditions that may influence stream chemistry at specific

locations along a stream, all candidate landscape predictor variables were expressed on a grid basis with a cell size of 30 m. This resolution was sufficient to conduct flowpath analyses for developing topographically determined streams from NHDPlus v2 data (<http://www.horizon-systems.com/nhdplus/>) and also to prepare the predictor variable datasets for ANC and BC_w regionalization. Values of predictors from the area contributing to each 30 m grid cell were upslope averaged, based on methodology described in McDonnell et al. (2012).

A two-stage hurdle modeling framework was used to model ANC across the study region. The first stage of the hurdle modeling approach identified streams with high buffering capacity (e.g., ANC > 100 µeq/L) where ecological impacts of anthropogenic acidic deposition are not expected to occur. The second stage provided continuous ANC predictions for those streams with ANC levels below which negative impacts are known to occur (< 100 µeq/L).

In the first stage of the hurdle modeling a binary random forest classification model was trained on all stream sites that had observed ANC (n = 2,225) to predict stream reaches with ANC > 100 µeq/L. Backwards elimination was used to select a parsimonious set of predictors. The fewest number of predictors was chosen while maintaining final accuracy within 10% of the full model. The second stage of the hurdle model consisted of a continuous linear regression model that was trained on streams with observed ANC < 100 µeq/L.

The continuous ANC model in the first version of EMDS was developed using a random forest modeling approach (Povak et al. 2013). However, the continuous ANC model development associated with the current iteration presented here has made use of additional stream chemistry measurements and a revised set of candidate predictor variables, using a multiple linear regression method rather than the random forest technique. This change was made because continuous ANC results based on random forest were biased high in the range of

ANC that is most sensitive to stream biota ($< 50 \mu\text{eq/L}$). Preliminary investigations during the current iteration showed that model performance metrics based on linear regression modeling were similar to those based on random forest, but the continuous ANC results from linear regression showed less bias for predicted ANC values less than $50 \mu\text{eq/L}$.

Continuous ANC models were developed with the *lm* function available in R v3.4.1. Models were derived based on a stepwise variable selection procedure with the variance inflation factor (VIF) determined for each predictor variable initially selected. To minimize overfitting, the predictor variable with highest VIF was removed, and the stepwise selection was re-run iteratively until all selected predictors had VIF below 4. An attempt to develop a global linear regression model to predict continuous ANC based on all sites with $\text{ANC} < 100 \mu\text{eq/L}$ ($n = 1,503$) resulted in a global ANC model with 20 predictor variables, adjusted $r^2 = 0.327$ ($p\text{-value} < 0.001$), and root mean squared error (RMSE) = $23.887 \mu\text{eq/L}$. Results for the global ANC model were considered unsatisfactory for characterizing the full study region. Thus, all sites within the study region were divided into either the northern or southern subregion based on above/below 37° latitude (**Appendix 3**). Each of these datasets were split into a ‘training’ dataset for model building while reserving 10% of the data as a ‘test’ dataset for evaluating predictive performance. Variable selection and model fitting for the Northern and Southern ANC models proceeded in the same manner as the global model with additional removal of some variables that showed a direction of influence (positive or negative) on the response variable that was counter-intuitive. All sites located within each subregion with $\text{ANC} < 100 \mu\text{eq/L}$ were included for estimating parameter coefficients for the final Northern and Southern ANC models and non-significant ($p > 0.05$) predictor variables were removed from the final models.

A multiple linear regression model for predicting BC_w was developed based on MAGIC calibrated BC_w at the 177 MAGIC model sites. The same set of candidate predictor variables and selection criteria that provided the basis for continuous ANC model development were also used for developing the regression model to predict BC_w throughout the full EMDS study region. After these criteria were applied, the six most significant predictors were relied on for estimating BC_w . Inclusion of additional predictors showed only minimal improvement in model performance while increasing model complexity for this relatively small sample size. This model was used to develop landscape-scale BC_w data to be used as input to the SSWC and SMB models. The BC_w data used for SSWC calculations were derived from the upslope-averaged predictor datasets. The BC_w data used for SMB calculations were derived based on the raw (i.e., non-upslope averaged) predictor datasets. The BC_w values used for SSWC calculations are representative of the full drainage area associated with the outlet of each catchment, whereas the BC_w values used for SMB are representative of average conditions only within each catchment boundary. The critical ANC leaching rate ($ANC_{le,crit}$; see SMB equation below) requires an estimate of nutrient base cation ($Ca + Mg + K$) weathering (Bc_w). The relationship between MAGIC modeled BC_w and Bc_w for only the three nutrient base cations ($r^2 = 0.93$) was used to estimate Bc_w from the landscape-scale predictions of BC_w according to:

$$Bc_w = 0.9012 * BC_w - 9.8874 \quad (1)$$

A second BC_w model was developed for predicting BC_w at sites that had measured stream water acid-base chemistry ($n = 2,225$). This model also relied on multiple linear regression and the same set of predictor variables that was used for the landscape scale BC_w model. This set of predictor variables included an approximation of BC_w according to the base cation flux balance ($BC_{w,FB}$), derived as:

$$BC_{w,FB} = BC_{stream} + Bc_{up} - BC_{dep} \quad (2)$$

where BC_{stream} is the stream water base cation flux, Bc_{up} is the watershed average nutrient base cation uptake (McNulty et al. 2007), and BC_{dep} is total deposition of base cations to the watershed.

For a given catchment, all available methods for measuring/estimating ANC and BC_w were used to map the final ANC and CL results. This was accomplished by differentially weighting each of the available estimates at a given location based on proportional area. The catchments associated with the topographically determined stream network tend to be quite small ($\sim 1 \text{ km}^2$) and most of the measured ANC sample sites and MAGIC model sites are drained by several topographically determined catchments. For these locations, the final values of ANC and BC_w associated with each catchment reflect an area-weighted average among predicted ANC and BC_w estimates at a given catchment and the measured/MAGIC modeled values at the nearest downstream sample/model site.

2.3.2 *Steady-State Critical Loads*

Critical loads of S deposition were determined with the steady-state water chemistry model (SSWC; Henriksen and Posch 2001) for protecting stream biota and with the simple mass balance model (SMB; Posch et al. 2001) for protecting terrestrial vegetation against acidification impacts:

SSWC

$$CL(S) = BC_{dep} - Cl_{dep} + BC_w - Bc_{up} - ANC_{limit} \quad (3)$$

SMB

$$CL(S) = BC_{dep} - Cl_{dep} + BC_w - Bc_{up} - ANC_{le,crit} \quad (4)$$

where Cl_{dep} is total chloride deposition, BC_w is soil mineral base cation weathering, BC_{up} is nutrient (Ca, Mg, and K) base cation uptake (McNulty et al. 2007), ANC_{limit} is the critical ANC stream flux based on a specified ANC concentration for protecting aquatic biota (e.g. $ANC = 50 \mu eq/L$), and $ANC_{le,crit}$ is the critical leaching of ANC based on a specified protective nutrient base cation to Al ratio in soil solution, described as:

$$ANC_{limit} = ANC_{crit} * Q \quad (5)$$

where, ANC_{crit} is the specified critical ANC threshold ($\mu eq/L$) for protecting aquatic biota (For example, $50 \mu eq/L$) and Q is watershed runoff (difference between precipitation and evapotranspiration; m/yr).

$$ANC_{le,crit} = -Q^{\frac{2}{3}} \cdot \left(1.5 \cdot \frac{BC_{dep} + BC_w - BC_{up}}{K_{gibb} \cdot \left(\frac{Bc}{Al}\right)_{crit}} \right)^{\frac{1}{3}} - 1.5 \cdot \frac{BC_{dep} + BC_w - BC_{up}}{\left(\frac{Bc}{Al}\right)_{crit}} \quad (6)$$

where, K_{gibb} is the gibbsite equilibrium constant and $(Bc/Al)_{crit}$ is the specified critical soil solution Bc/Al for protecting terrestrial vegetation (For example, 1 or 10).

The stream water NO_3^- concentration was interpolated throughout the EMDS study region (180 m grid resolution) from among the 2,225 measured water chemistry sites using an inverse distance weighted technique based on the nearest 12 stream sites to each grid cell. This was done for the purposes of developing an estimate of N leaching (N_{leach} , $meq/m^2/yr$), which is calculated as interpolated NO_3^- concentration ($\mu eq/L$) * runoff (m/yr), to include in the determination of aquatic CL exceedance. Including these estimates of N_{leach} into the CL exceedance calculation results in the “present-day” CL exceedance by incorporating the effect of ambient NO_3^- leaching on stream water acidity:

$$Exceedance = S_{dep} + N_{leach} - CL \quad (7)$$

where S_{dep} is the S deposition rate used for determining CL exceedance, N_{leach} is an estimate of N leaching. The NO_3^- leaching rate may change in the future and it is possible to explore future scenarios of CL exceedance based on different assumptions of expected future NO_3^- leaching.

Regional ANC, BC_w , and CL modeling results were developed for the full EMDS study region (**Figure 1**). This report presents results for the eight National Forest proclamation boundaries contained within the EMDS study region: Monongahela NF, George Washington NF, Jefferson NF, Cherokee NF, Pisgah NF, Nantahala NF, Chattahoochee NF, and the Andrew Pickens Ranger District of the Sumter NF. Critical load results from SSWC for protection of aquatic biota are based on input data derived from the full drainage area contributing to each stream site. Critical load results from SMB for protecting terrestrial vegetation are based on input data from only hillslope (i.e. non-stream) cells within a given catchment and are representative of average conditions within each catchment.

A critical ANC threshold of 50 $\mu\text{eq/L}$ was used for determining CLs with SSWC for all streams throughout the study region. A critical Bc/Al threshold of 1 and 10 were used for determining CLs with SMB for coniferous and deciduous forests, respectively (Cronan and Grigal 1995, Watmough et al. 2004). Critical $\text{Bc/Al} = 1$ was applied to catchments that contained coniferous forest types (Cronan and Grigal 1995). Only CLs for catchments that contained any amount of a deciduous forest type were based on a critical $\text{Bc/Al} = 10$. Although terrestrial CLs may not apply to non-forested catchments, a threshold $\text{Bc/Al} = 10$ was used to derive CLs for these areas under the assumption that acid-sensitive herbaceous/shrub vegetation may occur in these areas.

For aquatic CLs, catchments predicted to have “high” stream water ANC at the outlet according to the threshold ANC model were attributed as having “high” CL (i.e., not acid-

sensitive). Similarly, for terrestrial CLs, catchments with the majority of hillslope grid cells considered to have “high” drainage water ANC were attributed as having “high” CL.

3 MODELING OUTPUT

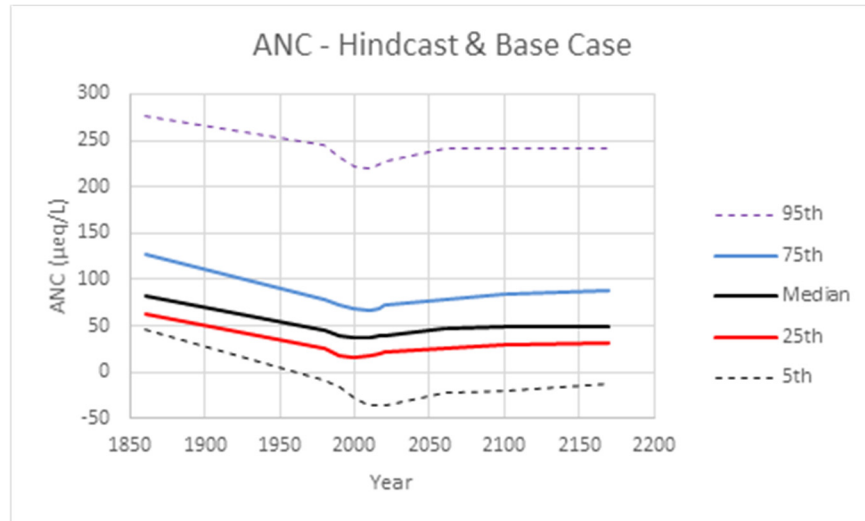
3.1 MAGIC Modeled Streams

3.1.1 Scenarios

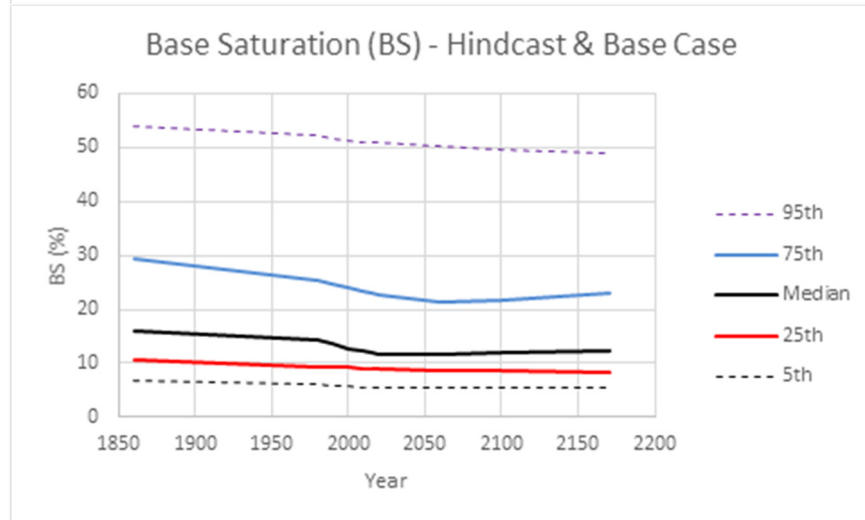
Stream water ANC and soil base saturation (BS) showed decreasing trends from year 1860 to ambient (2016) conditions (**Figure 3**). Stream sulfate consistently increased to approximately year 2000 and then decreased under the base case scenario for all sites. Most sites showed marginal ANC recovery under the base scenario, whereas BS continued to decline for the sites with pre-industrial BS < 10%. All of the MAGIC modeled stream sites (n = 177) were expected to have pre-industrial (year 1860) ANC of at least 30 µeq/L, with the exception of one site with estimated preindustrial ANC=29 µeq/L (**Table 1**). Due to the effects of anthropogenic S and N deposition, there were 70 streams (40%) with ANC below 30 µeq/L by the year 2016. Under the Base Case scenario, 24 streams were able to recover to ANC above 30 µeq/L and the Regional Haze scenario was expected to recover an additional 13 streams to greater than 30 µeq/L. Thirty-three streams were expected to remain below ANC = 30 µeq/L, even with the additional deposition reductions simulated with the Regional Haze scenario. An increase of 10% in reduced N deposition, beyond the effects of Regional Haze (RH + Red N), had little effect on future ANC. ANC scenario results for individual model sites are included in **Appendix 4**.

Soil BS was low (< 12%) for about one-third (n = 65) of the modeled sites in the year 1860, increasing to one-half (n = 89) under ambient conditions (**Table 2**). Although changes in future soil BS occurred, the deviations from ambient conditions were mostly too small to cause

a)



b)



c)

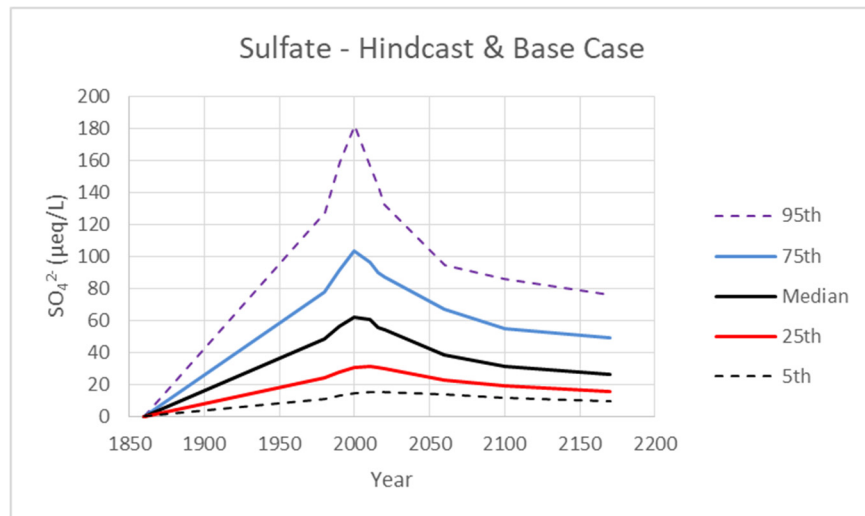


Figure 3. Trends in MAGIC modeled a) ANC, b) base saturation (BS), and c) stream sulfate from 1860 to 2170 among MAGIC sites ($n = 177$).

Table 1. Number of streams within various ANC classes according to MAGIC modeled pre-industrial (1860), ambient (2016), and future scenario (2100) ANC conditions.

Year (Scenario)	Stream ANC Class ($\mu\text{eq/L}$)				
	< 0	0 - 30	30 - 50	50 - 100	> 100
1860 (Hindcast)	0	1	18	89	69
2016 (Ambient)	28	42	41	38	28
2100 (Base Case)	17	29	44	52	35
2100 (RH)	12	21	47	57	40
2100 (RH + Red N)	12	21	48	56	40

Table 2. Number of catchments within various base saturation (BS; %) classes according to MAGIC modeled pre-industrial (1860), ambient (2016), and future scenario (2100) conditions.

Year (Scenario)	Soil BS Class (%)			
	0 - 12	12 to 20	20 to 50	50 - 100
1860 (Hindcast)	65	42	58	12
2016 (Ambient)	89	38	40	10
2100 (Base Case)	89	37	42	9
2100 (RH)	87	38	43	9
2100 (RH + Red N)	87	38	43	9

sites to shift from one class to another by the year 2100, regardless of the future deposition scenario. Base saturation scenario results for individual model sites are included in **Appendix 5**.

3.1.2 Target Loads

It was determined that approximately 17% of the MAGIC modeled streams ($n = 30$) were not able to attain ANC of 30 $\mu\text{eq/L}$ by year 2100, even if S deposition was reduced to zero (**Table 3**). These streams can be considered “can’t get there from here” with only S deposition reductions. According to the TL simulations based on an ANC criterion of 50 $\mu\text{eq/L}$, the proportion of modeled streams that can’t get there from here by the year 2100 increased to 44% ($n = 77$). Of these 77 streams, 19 had pre- industrial ANC < 50 $\mu\text{eq/L}$, so a more appropriate

Table 3. Number of streams within various classes of target loads of sulfur (S) deposition to attain a critical ANC criterion of 30 and 50 $\mu\text{eq/L}$ for endpoint years 2060, 2100, and 2170.

	Aquatic TL Class ($\text{meq/m}^2/\text{yr}$)					
	0	0 - 25	25-50	50 - 75	75-100	> 100
TL of S; ANC = 30 $\mu\text{eq/L}$						
Year 2060	30	26	22	29	22	48
Year 2100	30	26	22	29	22	48
Year 2170	25	22	40	35	20	35
TL of S; ANC = 50 $\mu\text{eq/L}$						
Year 2060	87	19	10	11	6	44
Year 2100	77	26	17	13	8	36
Year 2170	63	34	25	19	7	29

ANC criterion would be 30 $\mu\text{eq/L}$, which is near the minimum pre-industrial ANC among the 177 sites. However, the simulations suggested that only 5 of these 19 streams would be able to recover to ANC=30 $\mu\text{eq/L}$ by the year 2100.

Given that some streams were not able to recover to their pre-industrial ANC level, the TLs based on the criterion of pre-industrial ANC minus 10 $\mu\text{eq/L}$ can provide an indication of whether any of the streams that are “can’t get there from here” for ANC = 30 ($n = 14$) might come close to attaining this target. However, the modeling suggested that none of these 14 streams would recover to within 10 $\mu\text{eq/L}$ of pre-industrial ANC. This set of streams represents the most acid-sensitive watersheds among the modeled set, half of which are located on the Jefferson NF and the other half are located among the Cherokee NF, Pisgah NF, Nantahala NF, and Otter Creek/Dolly Sods Wilderness Area locations.

Sites for which the ANC criterion of 30 $\mu\text{eq/L}$ was attainable by year 2100 showed a relatively even spread among TLs classes (**Table 3**), ranging from greater than 0 to 100 $\text{meq/m}^2/\text{yr}$. This reflects a large range of acid sensitivity. As expected, TLs for attaining the more conservative ANC criterion of 50 $\mu\text{eq/L}$ were lower. A full list of TLs to reach ANC = 30 and 50 $\mu\text{eq/L}$ by the years 2060, 2100, and 2170 can be found in **Appendix 6**.

One-quarter of the streams ($n = 44$) were in exceedance of the TL to attain $ANC = 30$ $\mu\text{eq/L}$ by the year 2100 (**Table 4**). This number nearly doubled ($n = 86$) based on TLs and deposition to attain $ANC = 50$ $\mu\text{eq/L}$ by the same year.

Table 4. Number of streams in exceedance, not in exceedance, or uncertain with respect to exceedance of S target loads for critical ANC criteria of 30 and 50 $\mu\text{eq/L}$ and endpoint years 2060, 2100, and 2170 based on estimates of year 2016 S deposition. Exceedance was considered uncertain if S deposition was within 10 $\text{meq/m}^2/\text{yr}$ of the critical load.

	No Exceedance	Exceedance Uncertain	Exceedance
TL of S Exceedance; $ANC = 30$ $\mu\text{eq/L}$			
Year 2060	121	6	50
Year 2100	126	7	44
Year 2170	128	15	34
TL of S Exceedance; $ANC = 50$ $\mu\text{eq/L}$			
Year 2060	73	12	92
Year 2100	76	15	86
Year 2170	84	14	79

3.2 National Forest-Wide Streams

3.2.1 Regional ANC Model

The model for predicting the locations of streams having a high ANC of > 100 $\mu\text{eq/L}$ was 78% accurate based on the training data. Predictor variables included soil percent clay, siliceous lithology, S deposition, annual precipitation, soil percent sand, and base flow index. The continuous ANC model for the northern subregion resulted in 9 predictor variables, each with $VIF < 3.5$. The southern ANC model resulted in 15 predictor variables each with $VIF < 2.4$. The northern ANC model showed a better fit to the data than the southern model, explaining more than 50% of the variation ($p\text{-value} < 0.001$) in observed northern ANC as opposed to approximately 25% in the south (**Figures 4 and 5**). Primary predictor variables for both models included siliceous lithology, soil percent sand, coniferous forest, and aspects of climate. Final model descriptions are included in **Appendix 7**.

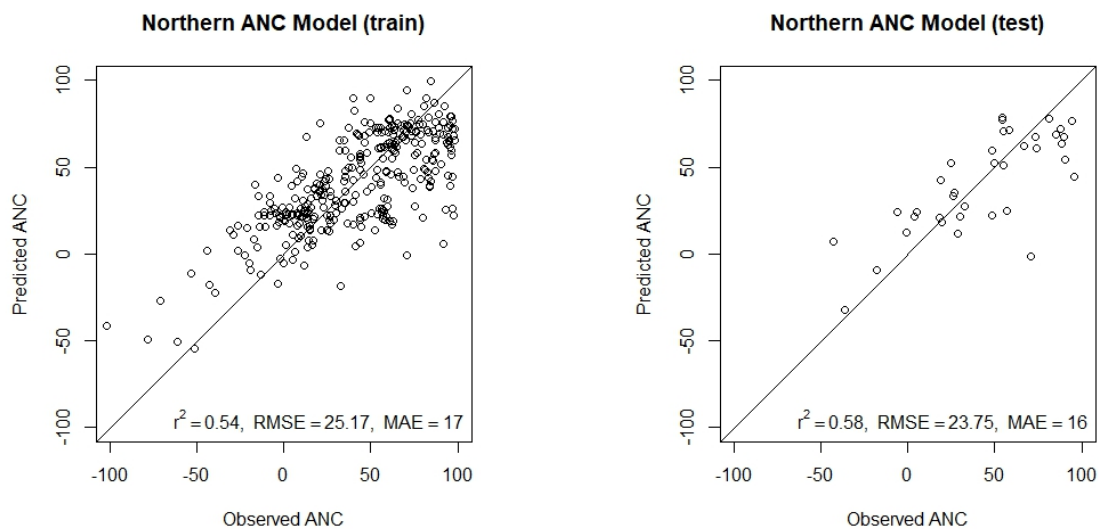


Figure 4. Northern ANC model results for a) training data and b) test data showing predicted versus observed ANC (μeq/L; open circles) and 1:1 line (solid black line). RMSE is root mean squared error and MAE is mean absolute error.

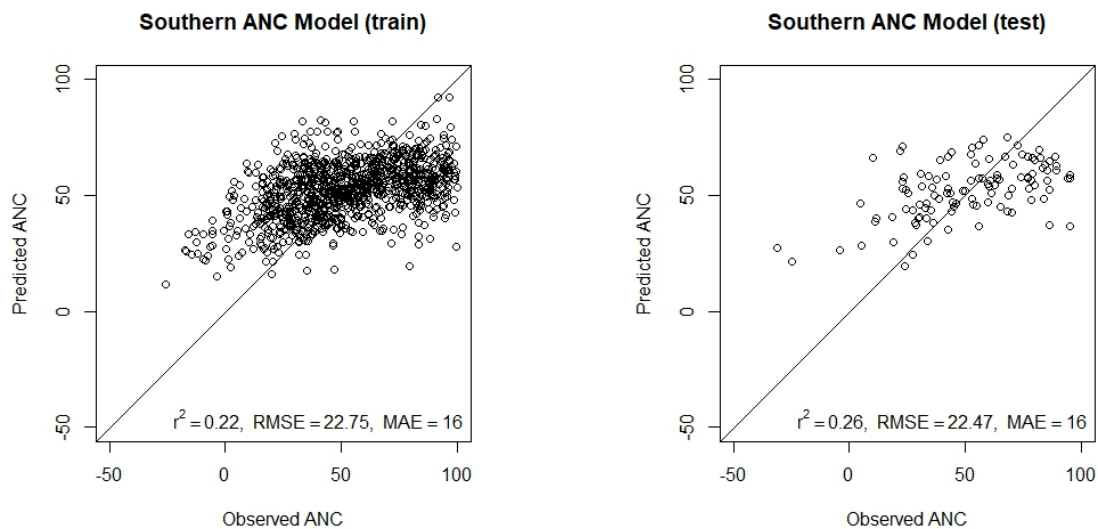


Figure 5. Southern ANC model results for a) training data and b) test data showing predicted versus observed ANC (μeq/L; open circles) and 1:1 line (solid black line). RMSE is root mean squared error and MAE is mean absolute error.

Regional predictions of recent stream ANC were heterogeneous among and within the NFs, with streams predicted to have ANC < 100 µeq/L interspersed with those expected to have ANC > 100 µeq/L (**Figure 6**). The Monongahela NF, followed by the George Washington and Jefferson NFs, had the greatest percent area with low (< 30 µeq/L) ANC at about 20%, 9%, and 9%, respectively (**Table 5**).

Table 5. Area and percent of each national forest included within designated ambient stream water acid neutralizing capacity (ANC; µeq/L) classes based upon the continuous ANC regression model.

Forest	Stream ANC Class (µeq/L)									
	< 0		0 - 30		30 - 50		50 - 100		> 100	
	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%
Monongahela	436.8	6.3	961.6	13.9	488.0	7.1	1566.4	22.7	3441.7	49.9
George Washington	93.4	1.3	520.0	7.2	561.7	7.7	1162.3	16.0	4935.2	67.9
Jefferson	35.4	0.5	555.7	8.1	1197.2	17.4	2003.8	29.2	3080.9	44.8
Cherokee	0.0	0.0	40.1	0.8	300.7	6.1	2492.9	50.2	2133.1	42.9
Pisgah	0.5	0.0	21.0	0.4	227.4	4.8	3166.3	67.4	1280.6	27.3
Nantahala	0.0	0.0	14.7	0.3	36.1	0.7	3465.3	64.0	1900.5	35.1
Chattahoochee	0.0	0.0	35.1	0.6	145.0	2.4	3196.2	52.0	2774.7	45.1
Sumter	0.0	0.0	0.0	0.0	0.0	0.0	178.6	31.7	384.7	68.3

3.2.2 Regional BC_w Model

The landscape only and the landscape + water chemistry BC_w models explained 35% and 96% of the variation in MAGIC calibrated BC_w, respectively (**Figure 7**). Landscape variables included in the BC_w models included S deposition, siliceous lithology, soil pH, aspects of soil drainage/wetness characteristics, and air temperature. Final model descriptions are included in **Appendix 8**. Regional predictions of BC_w were heterogeneous across the landscape with some areas showing very low (< 25 meq/m²/yr) BC_w rates (**Table 6, Figure 8**). The Jefferson NF had the most percent area with low (< 50 meq/m²/yr) BC_w.

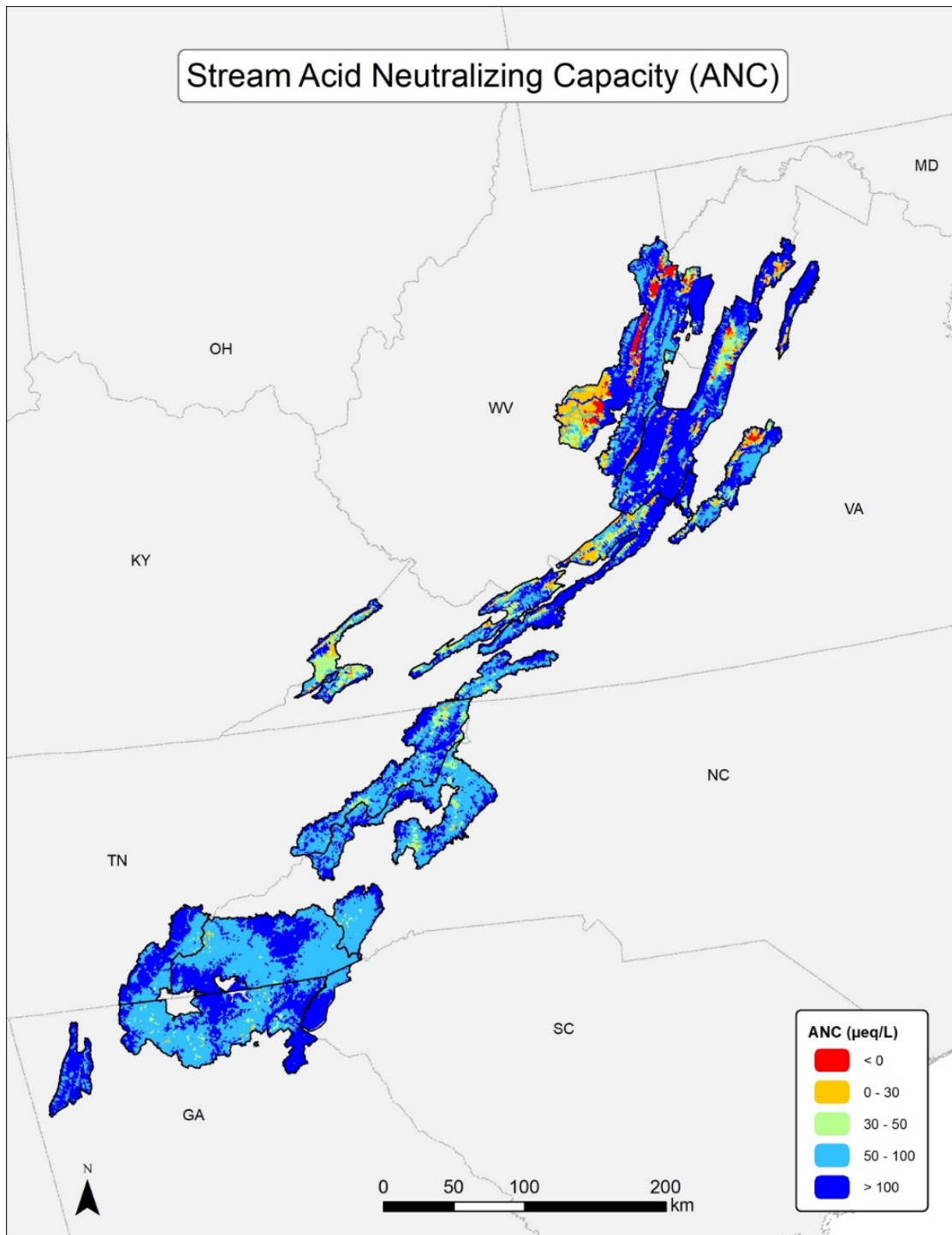


Figure 6. Spatial variation in extrapolated acid neutralizing capacity (ANC) among the southern Appalachian national forests.

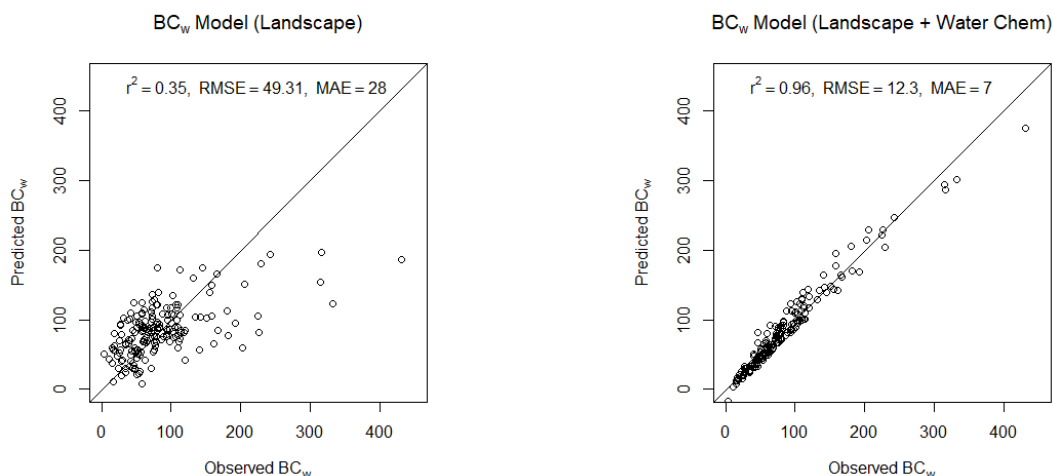


Figure 7. Predicted versus observed (MAGIC modeled) base cation weathering (BC_w) for the regression models based on a) only landscape variables and b) landscape + water chemistry variables. The solid black line represents the 1:1 line. RMSE is root mean squared error and MAE is mean absolute error.

Table 6. Area and percent of each national forest included within designated base cation weathering (BC_w ; meq/m²/yr) classes.

Forest	Soil BC_w Class (meq/m ² /yr)									
	< 25		25 - 50		50 - 100		100 - 200		> 200 or High BC_w	
	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%
Monongahela	29.9	0.4	444.0	6.4	1819.4	26.4	1341.4	19.5	3259.8	47.3
George Washington	79.3	1.1	363.8	5.0	1315.5	18.1	689.3	9.5	4824.8	66.3
Jefferson	162.6	2.4	1054.3	15.3	2194.5	31.9	502.0	7.3	2959.6	43.1
Cherokee	18.4	0.4	125.9	2.5	1616.3	32.5	1206.2	24.3	2000.1	40.3
Pisgah	13.1	0.3	74.7	1.6	2373.9	50.6	1025.1	21.8	1208.9	25.7
Nantahala	0.2	0.0	52.3	1.0	2965.7	54.8	673.6	12.4	1724.8	31.8
Chattahoochee	3.5	0.1	33.6	0.5	680.6	11.1	2861.7	46.5	2571.7	41.8
Sumter		0.0		0.0	48.5	8.6	149.7	26.6	365.0	64.8

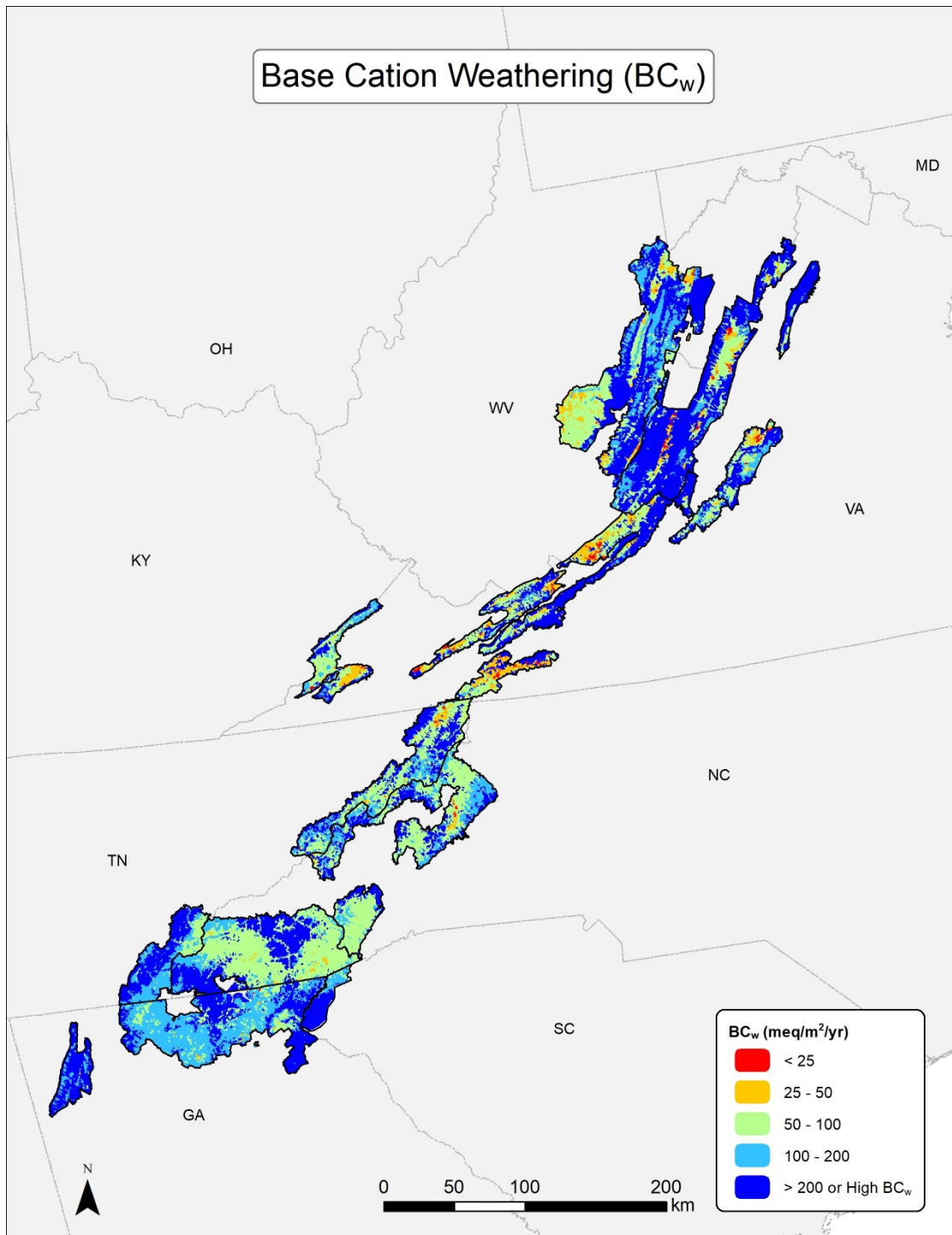


Figure 8. Spatial variation in extrapolated base cation weathering (BC_w) among the southern Appalachian national forests.

3.2.3 Critical Loads of S Deposition and Exceedance

3.2.3.1 Aquatic

Critical loads of S deposition derived from the SSWC model for the protection of aquatic biota were relatively low for many areas located within National Forest boundaries (**Figure 9, Table 7**). The extrapolated NO_3^- concentration showed values less than $10 \mu\text{eq/L}$ within the majority of the National Forest boundaries (**Table 8, Figure 10**). However, elevated stream water NO_3^- concentrations were expected within 19%, 15%, and 21% of the George Washington, Cherokee, and Pisgah National Forests, respectively. As expected, CL exceedance including NO_3^- leaching (orange and red areas shown in **Figure 11a**) was greater than without including the effect of NO_3^- leaching (**Figure 11b**). More than one-quarter of the streams in the Nantahala NF were expected to be in exceedance of the aquatic CL for attaining $\text{ANC} = 50 \mu\text{eq/L}$ or greater, meaning that the ambient deposition is higher than the CL, without considering the effect of the ambient NO_3^- leaching (**Table 9**) and nearly 30% were in exceedance when including the effect of NO_3^- leaching in the exceedance calculation (**Table 10**). Other NFs with a substantial proportion ($> 18\%$) of area in exceedance of the CL included Monongahela, Jefferson, and Pisgah NFs (**Table 10**). These areas of exceedance tended to have relatively low weathering rates, in addition to being subjected to elevated S deposition.

3.2.3.2 Terrestrial

Critical loads for the protection of terrestrial biota derived from the SMB model (**Figure 12, Table 11**), were generally higher than those determined for aquatic systems. This is likely because stream acid-base chemistry tends to be more sensitive than soil acid-base chemistry and therefore often have lower CLs (Sullivan 2017). Most of the terrestrial CLs $< 50 \text{ meq/m}^2/\text{yr}$ were found on the Jefferson NF (604 km^2 ; about 9%). Very little area within the NFs was considered

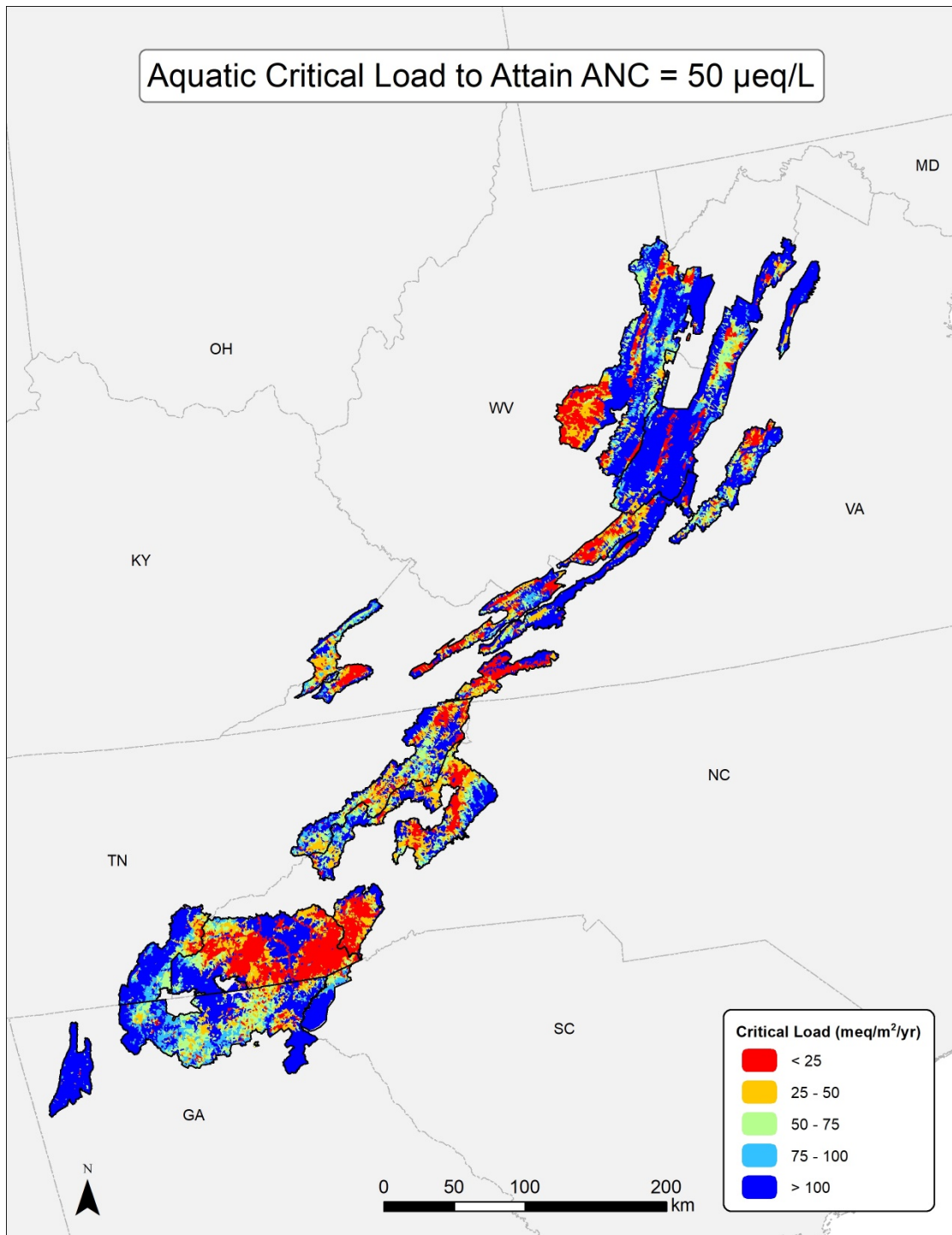


Figure 9. Spatial variation in aquatic critical loads of S deposition among the southern Appalachian national forests.

Table 7. Area and percent of each national forest included within designated aquatic critical load (CL; meq/m²/yr) classes.

Forest	Aquatic CL Class (meq/m ² /yr)									
	< 25		25 - 50		50 - 75		75 - 100		> 100	
	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%
Monongahela	1143.4	16.6	844.0	12.2	740.0	10.7	627.6	9.1	3539.5	51.3
George Washington	514.1	7.1	528.2	7.3	809.4	11.1	370.3	5.1	5050.8	69.4
Jefferson	1409.0	20.5	1262.5	18.4	802.5	11.7	350.1	5.1	3048.8	44.4
Cherokee	453.9	9.1	930.3	18.7	924.2	18.6	481.5	9.7	2176.9	43.8
Pisgah	1118.3	23.8	1258.2	26.8	679.0	14.5	234.1	5.0	1406.1	29.9
Nantahala	2192.8	40.5	950.1	17.5	383.1	7.1	132.2	2.4	1758.4	32.5
Chattahoochee	229.4	3.7	652.9	10.6	1183.1	19.2	856.5	13.9	3229.1	52.5
Sumter	28.3	5.0	44.3	7.9	48.8	8.7	74.3	13.2	367.5	65.2

Table 8. Area and percent of each national forest included within designated stream water nitrate (NO₃⁻; µeq/L) classes.

Forest	Stream NO ₃ ⁻ Class (µeq/L)									
	< 5		5 - 10		10 - 25		25 - 50		> 50	
	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%
Monongahela	6839.4	99.2	39.5	0.6	15.5	0.2	0.1	0.0		0.0
George Washington	4078.9	56.1	1813.0	24.9	1335.1	18.4	45.8	0.6		0.0
Jefferson	5317.9	77.4	1130.8	16.5	338.9	4.9	77.3	1.1	8.1	0.1
Cherokee	3201.7	64.5	1046.9	21.1	554.7	11.2	141.3	2.8	22.2	0.4
Pisgah	2926.6	62.3	761.1	16.2	619.0	13.2	367.8	7.8	21.2	0.5
Nantahala	3994.4	73.7	1174.4	21.7	247.7	4.6		0.0		0.0
Chattahoochee	5072.4	82.5	669.4	10.9	370.7	6.0	33.7	0.5	4.8	0.1
Sumter	508.8	90.3	52.8	9.4	1.7	0.3		0.0		0.0

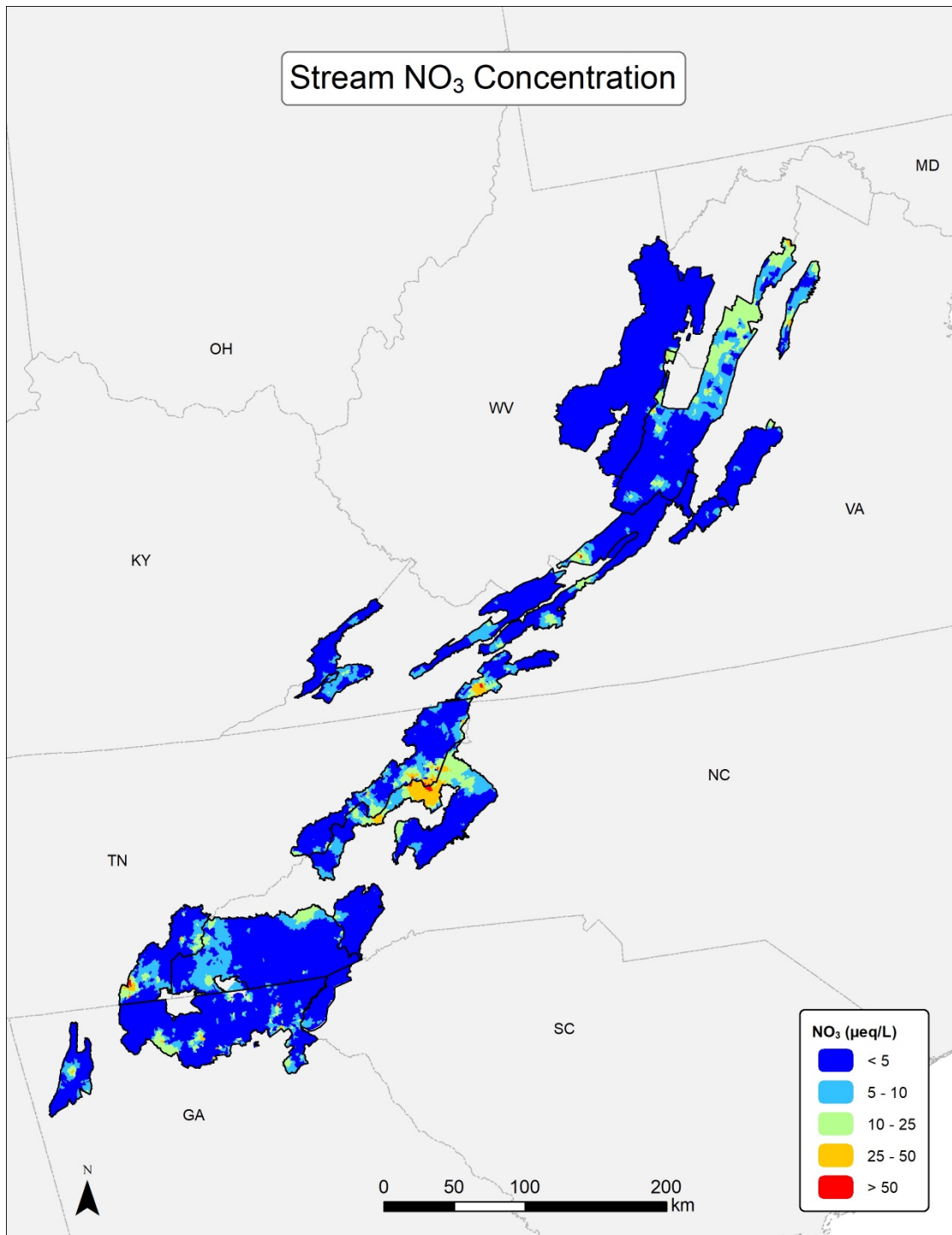


Figure 10. Spatial variation in extrapolated stream nitrate (NO_3^-) concentration among the southern Appalachian national forests.

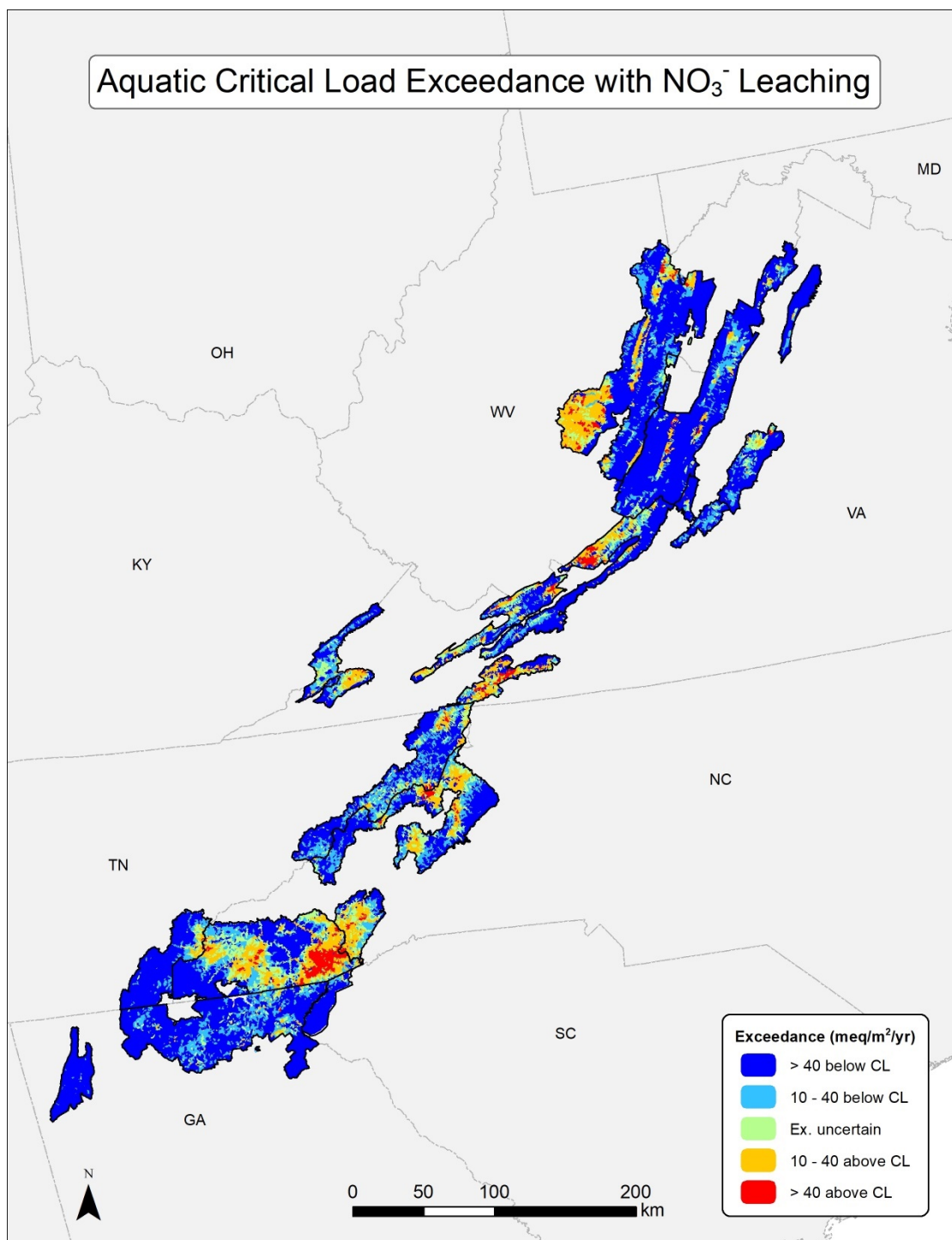


Figure 11a. Spatial variation in aquatic S critical load exceedance among the southern Appalachian national forests with the effect of ambient NO_3^- leaching.

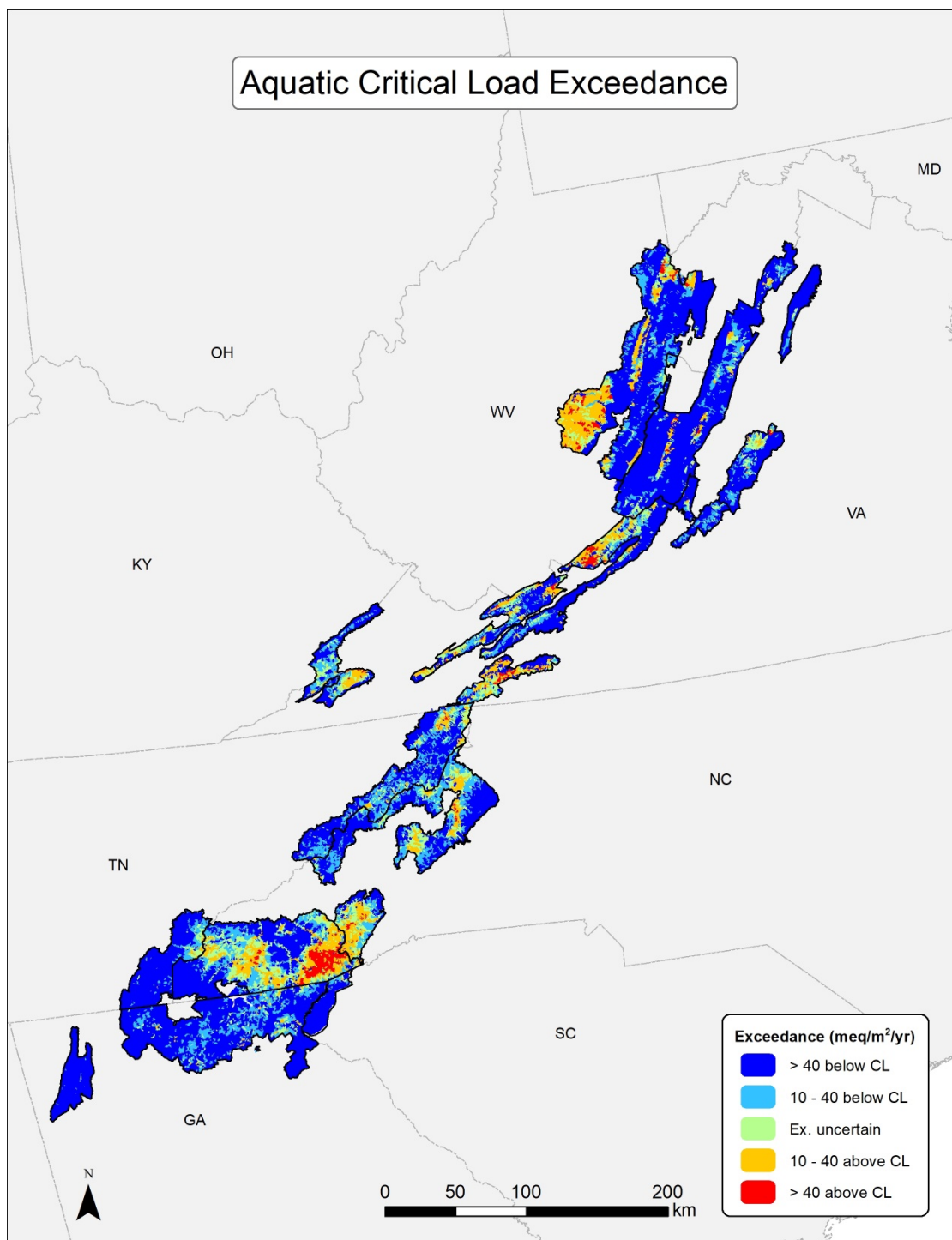


Figure 11b. Spatial variation in aquatic S critical load exceedance among the southern Appalachian national forests without the effect of ambient NO_3^- leaching.

Table 9. Area and percent of each national forest included within designated aquatic critical load (CL) exceedance (meq/m²/yr) classes for attaining stream water ANC = 50 µeq/L.

Forest	Aquatic CL Exceedance Class (meq/m ² /yr)									
	More than 40 Below the CL		Between 40 and 10 Below the CL		Exceedance Uncertain		Between 10 and 40 Above the CL		More than 40 Above the TL	
	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%
Monongahela	4151.6	60.2	827.4	12.0	509.9	7.4	1224.3	17.8	181.4	2.6
George Washington	5835.9	80.2	789.3	10.9	409.8	5.6	213.7	2.9	24.0	0.3
Jefferson	3584.4	52.2	1134.7	16.5	1018.4	14.8	945.5	13.8	189.9	2.8
Cherokee	3213.5	64.7	1146.7	23.1	400.8	8.1	194.2	3.9	11.6	0.2
Pisgah	1999.7	42.6	1225.3	26.1	799.3	17.0	623.6	13.3	47.8	1.0
Nantahala	2112.0	39.0	877.4	16.2	1059.4	19.6	992.8	18.3	375.1	6.9
Chattahoochee	4847.2	78.8	1016.5	16.5	214.8	3.5	71.7	1.2	0.8	0.0
Sumter	478.3	84.9	50.5	9.0	27.3	4.9	7.2	1.3		0.0

Table 10. Area and percent of each national forest included within designated aquatic critical load (CL) exceedance (meq/m²/yr) classes considering the effect of nitrate (NO₃⁻) leaching.

Forest	Aquatic CL Exceedance (with NO ₃ ⁻ Leaching) Class (meq/m ² /yr)									
	More than 40 Below the CL		Between 40 and 10 Below the CL		Exceedance Uncertain		Between 10 and 40 Above the CL		More than 40 Above the TL	
	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%
Monongahela	4130.9	59.9	842.6	12.2	513.5	7.4	1226.1	17.8	181.4	2.6
George Washington	5714.7	78.6	846.5	11.6	440.0	6.0	245.3	3.4	26.2	0.4
Jefferson	3536.6	51.5	1069.6	15.6	987.0	14.4	1017.9	14.8	261.8	3.8
Cherokee	3060.5	61.6	1106.5	22.3	466.0	9.4	299.3	6.0	34.5	0.7
Pisgah	1900.1	40.5	969.8	20.7	780.8	16.6	931.9	19.8	113.1	2.4
Nantahala	2032.8	37.5	758.5	14.0	1030.9	19.0	1147.1	21.2	447.2	8.3
Chattahoochee	4711.1	76.6	1076.5	17.5	258.8	4.2	100.8	1.6	3.7	0.1
Sumter	477.2	84.7	51.1	9.1	26.8	4.8	8.1	1.4		0.0

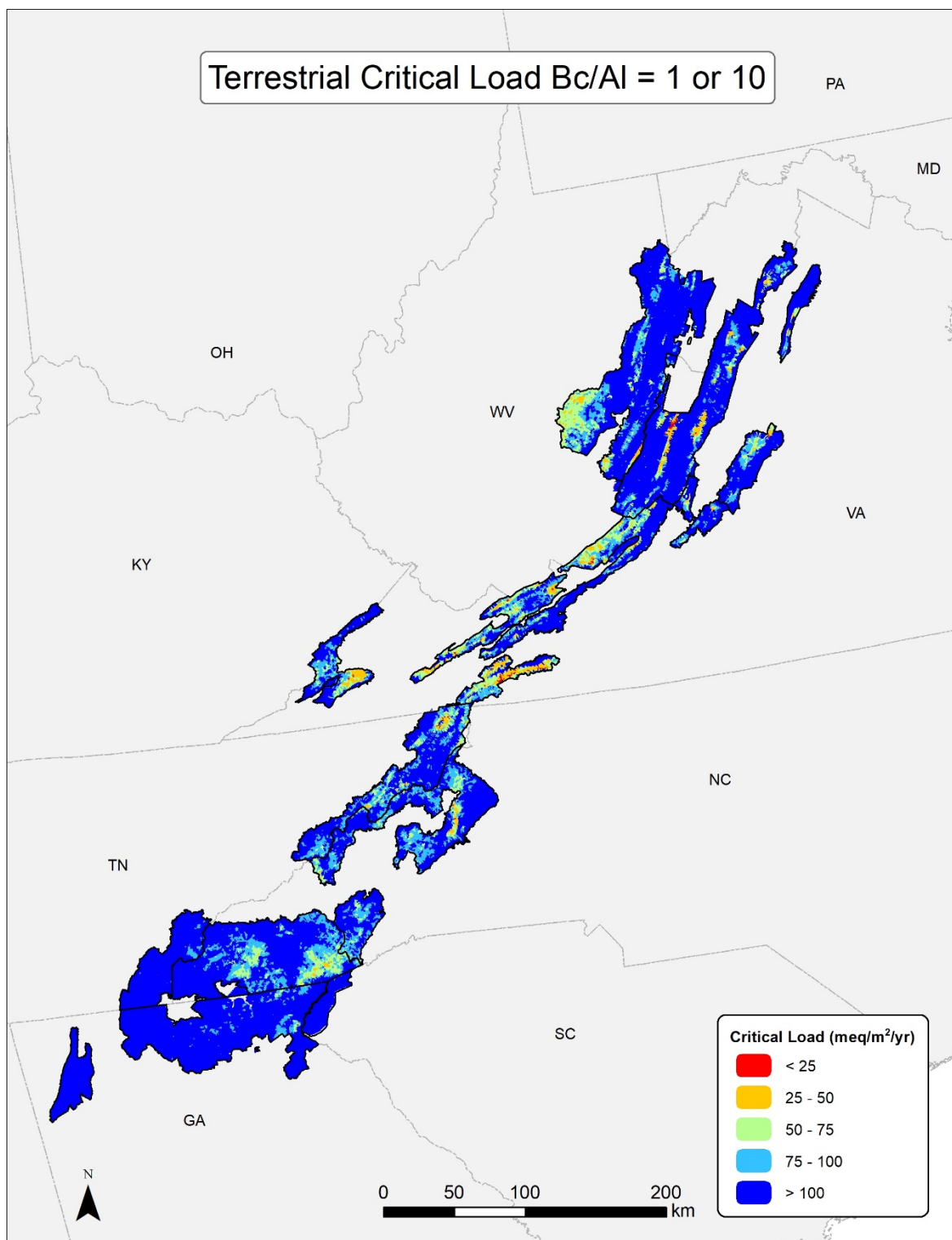


Figure 12. Spatial variation in terrestrial critical loads of S deposition among the southern Appalachian national forests.

Table 11. Area and percent of each national forest included within designated terrestrial critical load (CL; meq/m²/yr) classes for attaining soil solution nutrient base cation to aluminum (Bc/Al) = 1 or 10 for the protection of coniferous and deciduous trees, respectively.

Forest	Terrestrial CL Class (meq/m ² /yr)									
	< 25		25 - 50		50 - 75		75 - 100		> 100	
	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%
Monongahela	5.4	0.1	123.5	1.8	782.1	11.3	958.4	13.9	5025.2	72.9
George Washington	23.1	0.3	263.4	3.6	416.3	5.7	724.0	10.0	5845.9	80.4
Jefferson	50.7	0.7	558.3	8.1	1213.2	17.7	1422.2	20.7	3628.5	52.8
Cherokee	3.9	0.1	69.1	1.4	287.6	5.8	800.0	16.1	3806.2	76.6
Pisgah	3.2	0.1	53.7	1.1	377.2	8.0	1261.9	26.9	2999.7	63.9
Nantahala	0.7	0.0	38.2	0.7	511.9	9.5	1236.1	22.8	3629.7	67.0
Chattahoochee	0.2	0.0	2.4	0.0	39.3	0.6	271.5	4.4	5837.6	94.9
Sumter		0.0		0.0		0.0	2.0	0.4	561.2	99.6

to be in exceedance of terrestrial CLs (**Figure 13, Table 12**). This result suggests that recent deposition may be low enough to protect forest trees from the toxic effects of Al, but still too high to attain ANC = 50 µeq/L at many stream locations.

Currently, the EMDS system for addressing CLs of atmospheric deposition only includes data for evaluating exceedance of aquatic CLs. The back-end database has been developed in a manner that facilitates the incorporation of the newly developed terrestrial CLs from this study into the EMDS system. We recommend adding terrestrial CLs as a third category of ecosystem impact, as shown in **Figure 14**. In addition, any EMDS updates might also incorporate temperature impacts on brook trout (McDonnell et al. 2015).

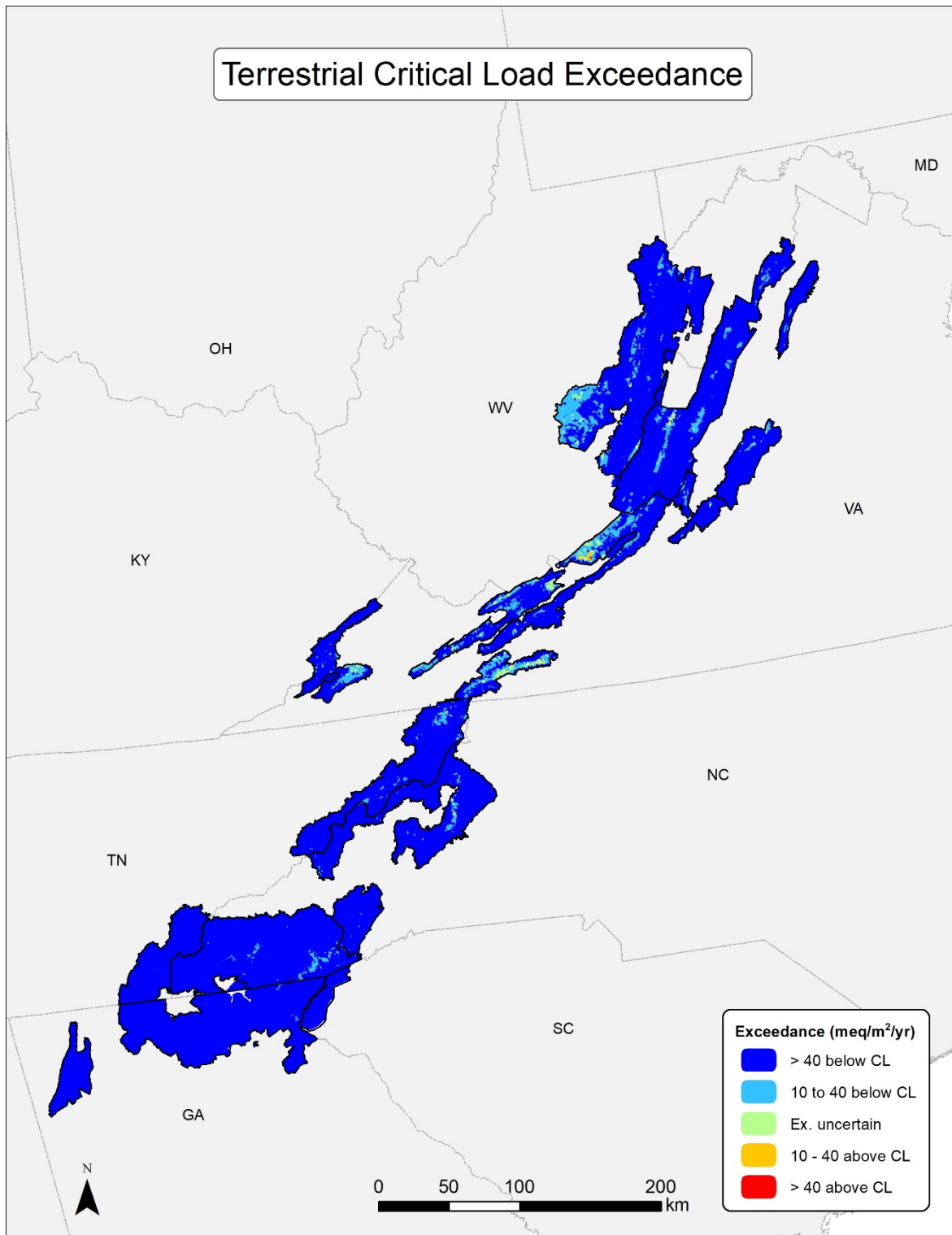


Figure 13. Spatial variation in terrestrial S critical load exceedance among the southern Appalachian national forests without the effect of ambient NO_3^- leaching.

Table 12. Area and percent of each national forest included within designated terrestrial critical load (CL) exceedance (meq/m²/yr) classes.

Forest	Terrestrial CL Exceedance Class (meq/m ² /yr)									
	More than 40 Below the CL		Between 40 and 10 Below the CL		Exceedance Uncertain		Between 10 and 40 Above the CL		More than 40 Above the TL	
	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%
Monongahela	5853.6	84.9	971.6	14.1	68.7	1.0	0.6	0.0		0.0
George Washington	6827.7	93.9	402.0	5.5	38.0	0.5	5.1	0.1	0.0	0.0
Jefferson	5344.2	77.8	1228.7	17.9	265.2	3.9	32.1	0.5	2.6	0.0
Cherokee	4840.5	97.5	119.6	2.4	6.6	0.1	0.2	0.0		0.0
Pisgah	4576.8	97.5	108.0	2.3	10.8	0.2	0.0	0.0		0.0
Nantahala	5273.9	97.4	142.0	2.6	0.3	0.0	0.4	0.0		0.0
Chattahoochee	6138.8	99.8	12.0	0.2	0.2	0.0	0.1	0.0		0.0
Sumter	563.2	100.0		0.0		0.0		0.0		0.0

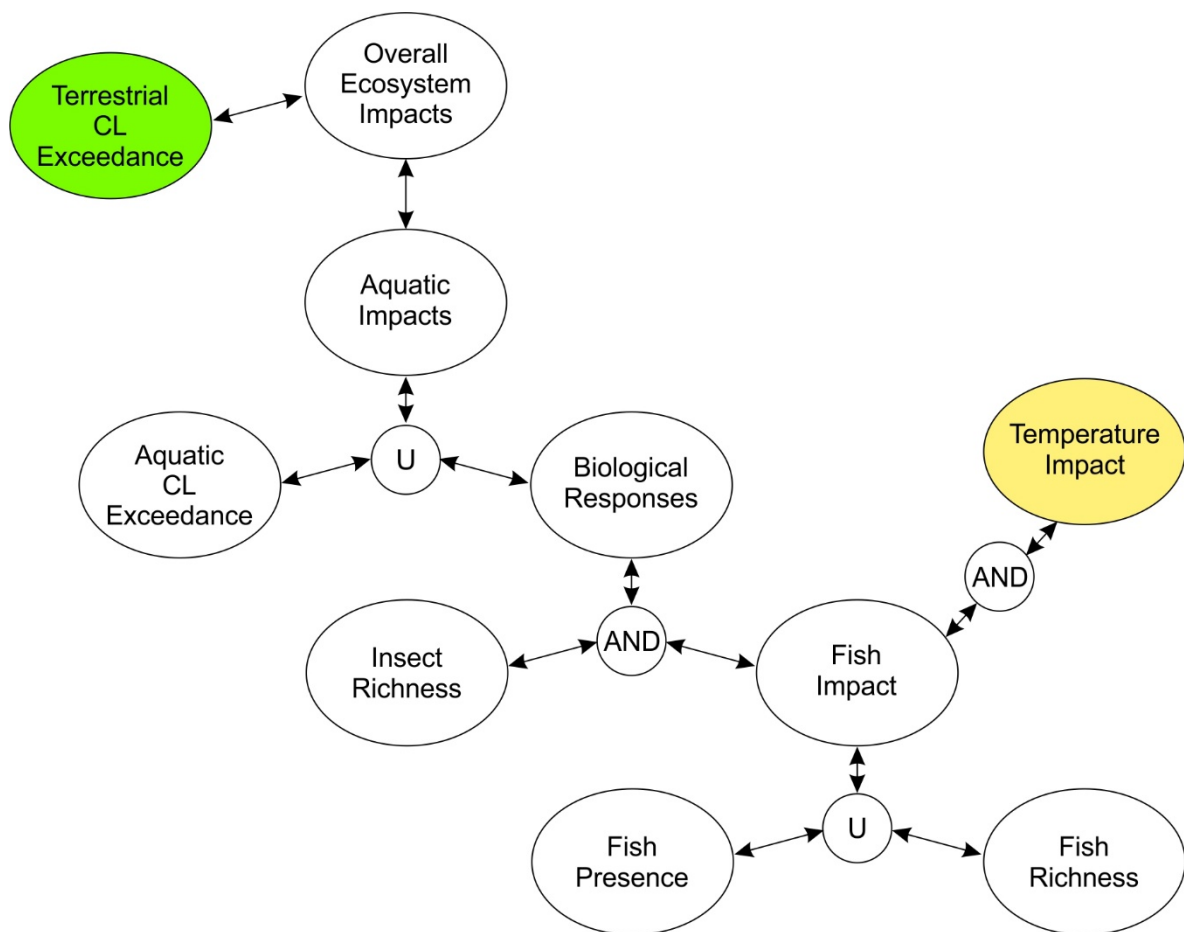


Figure 14. Proposed pathway for inclusion of terrestrial critical loads (CLs) and temperature impacts to brook trout into the existing EMDS system for evaluating aquatic impacts from atmospheric S deposition.

4 DISCUSSION AND MANAGEMENT IMPLICATIONS

Using dynamic modeling and mass balance approaches, we evaluated the potential effect of historical, ambient, and future acidic deposition on terrestrial and aquatic ecosystems within National Forest proclamation boundaries. Scenario results from dynamic modeling indicated that stream ANC at locations throughout the study area have deteriorated from pre-industrial conditions to levels sufficient to have caused negative impacts on aquatic biota. Future reductions in atmospheric N and S deposition are expected to help these systems recover towards pre-industrial conditions. However, full recovery is not anticipated by the year 2100. At present, S deposition rates are higher than stream systems can tolerate and remain supportive of healthy aquatic communities in many areas. Sulfur deposition rates have been on a steady decline and the extent of CL exceedance among National Forests is expected to reduce if these declines continue. However, if stream nitrate concentrations increase in the future, these exceedance reductions due to decreased S deposition may be at least partially offset by increased N leaching.

Results show generally low risk for acidification impact to terrestrial vegetation as estimated by the SMB model. Soil based thresholds for acidification impact are not well known and it is possible that soil base cation depletion from human-caused acidic deposition has made forests more susceptible to impacts from disturbances such as insect infestations and drought (McNulty and Boggs 2010). So, while Al toxicity does not appear to be an immediate threat, base cations reserves in the soil may be insufficient to support the long-term health of some terrestrial species.

Stream ANC is an indicator of the ability of stream water to buffer strong acids and is directly related to soil conditions, geology, BC_w rates, slope position, and other factors. With stream ANC in the range of 50 to 100 $\mu\text{eq/L}$, moderate effects on macroinvertebrates and fish species richness can occur. Brook trout populations should be sustainable at $ANC > 50 \mu\text{eq/L}$ if

other environmental factors are favorable (Cosby et al. 2006, Sullivan et al. 2006). In 1860, 89% of the 177 sites evaluated with MAGIC had ANC at or above 50 $\mu\text{eq/L}$, but that number declined to 37% by 2016. If deposition remains constant at recent levels (mean of 2013-2015) then some improvements are likely and 49% of the modeled streams may attain an ANC of 50 $\mu\text{eq/L}$ or above by year 2100. Significant reductions in deposition are anticipated from implementation of the Regional Haze Rule and that may increase the number of modeled streams above ANC = 50 $\mu\text{eq/L}$ from 49% to 55%. This value remains well below the historical high (89%) estimated for the year 1860.

Within the full extent of the proclamation boundaries (i.e. beyond the boundaries of the MAGIC watersheds), we estimated that all National Forests are expected to have more than 70% of the catchment area with ambient ANC of 50 $\mu\text{eq/L}$ or higher (Table 5), with the Monongahela having the lowest amount of area (72.6%) with ANC greater than 50 $\mu\text{eq/L}$ and the Sumter having the highest (100%). As such, stream acidity is a concern only for relatively small portions of the National Forests evaluated in this study. Threshold ANC modeling was robust (78% accuracy) for determining which areas are expected to have above/below ANC = 100 $\mu\text{eq/L}$. Although the two models for predicting continuous ANC for areas expected to have ANC less than 100 $\mu\text{eq/L}$ are highly significant ($p < 0.001$), the northern model explained 54% of the variation in stream ANC, while the southern model only explained 22% of the variation (Appendix 7). Therefore, land managers should rely on the threshold ANC results (shown in Figure 6) for understanding which portions of a National Forest are likely to have acid-sensitive or acid-impacted streams. If greater certainty in predicted ANC is required prior to project implementation, additional water chemistry samples can be collected to verify the model results.

We used a threshold of concern for streams to achieve $\text{ANC} = 50 \mu\text{eq/L}$ to determine the CLs and TLs in this study. However, attainment of stream $\text{ANC} = 50 \mu\text{eq/L}$ may not be possible for some catchments because they did not have ANC that high even during pre-industrial times. MAGIC estimated that 11% of the 177 modeled streams ($n = 19$) had ANC below $50 \mu\text{eq/L}$ in year 1860, with the lowest pre-industrial value of $29 \mu\text{eq/L}$ for a catchment on the Jefferson National Forest. Continued future S deposition at 2016 levels would prevent 48% of the MAGIC locations from reaching $\text{ANC} = 50 \mu\text{eq/L}$ by 2100 (**Table 4**). Of the nineteen streams with ANC less than $50 \mu\text{eq/L}$ in 1860, only 5 of these streams were predicted to attain $\text{ANC} = 30 \mu\text{eq/L}$ or higher by 2100. For western Virginia in the year 1851, Bulger et al. (2000) estimated that 82% of brook trout streams had ANC above $50 \mu\text{eq/L}$, with the remainder between 20 and $50 \mu\text{eq/L}$. While $\text{ANC} = 50$ is a useful threshold for many circumstances, it is not attainable at some locations and certain areas will require a more careful examination to determine appropriate chemical thresholds.

There is concern for streams with ANC below $50 \mu\text{eq/L}$, in part because they are potentially susceptible to episodic acidification (Robison et al. 2013). Following some storm events, an episodic pulse of acidification can cause a substantial decrease in stream ANC (Lawrence et al. 2015) in combination with a decrease in pH and an increase in Al. Both low pH and high Al concentration can be toxic to aquatic biota (Baker et al. 1996, Bulger et al. 2000). Bulger et al. (2000) reported that some aquatic species are extremely sensitive to acidification and can be affected at ANC between 20 and $50 \mu\text{eq/L}$. At ANC concentrations less than $20 \mu\text{eq/L}$, stream acidity and/or Al concentration can be lethal to brook trout. In addition, Smith and Voshell (2013) reported that there was a sharp decline in the abundance of acid sensitive

Ephemeroptera macroinvertebrates below ANC = 20 $\mu\text{eq/L}$ on the George Washington and Jefferson National Forests.

It is important to estimate the level of S deposition that the ecosystem can tolerate before there is harm to terrestrial and/or aquatic resources (i.e., the CL) on the National Forests. There are also some locations (such as Roan Mountain on the Cherokee and Pisgah National Forests) where N deposition is contributing to high stream nitrate concentrations ($> 25 \mu\text{eq/L}$, **Table 8** and **Figure 10**). Between 1.4% and 29.6% of the area within the National Forests boundaries is in exceedance of the CL of S deposition in the presence of ambient nitrate leaching. National Forests with aquatic CL exceedance of more than 15% of the area were the Nantahala (29.6%), Pisgah (22.2%), Monongahela (20.4%) and Jefferson (18.6%) (**Table 10**).

Sulfur is the primary acidifying agent in the National Forests of the southern Appalachian Mountains (Sullivan et al. 2011c) and S deposition has decreased markedly in recent decades⁴. However, the extent of future soil S retention/release in response to future deposition scenarios is not fully known. MAGIC results show a range in predicted stream SO_4^{2-} concentrations, suggesting spatial variation in S deposition and/or S retention. Rice et al. (2014) estimated the year when catchments in the Southern Appalachians will crossover from net retainer to net releaser of SO_4^{2-} . For one location within the Chattahoochee National Forest, the soils are likely to continue retaining most of the incoming S deposition in future years. The predicted crossover year for three watersheds on the Monongahela National Forest ranged between 2006 and 2011. Further south on the Nantahala National Forest the range was 2023 to 2025 with an upper crossover estimate of 2039 to 2038. Increased SO_4^{2-} release from the soils will result in

⁴ For example, the trend in wet sulfur and wet total nitrogen for the Pisgah National Forest is found at: <https://webcam.srs.fs.fed.us/graphs/dep/index.php?state=nc&forest=pisg&wilderness=none>. To retrieve the wet deposition trend results for the other National Forests then use the drop down menus on the webpage.

additional leaching of soil base cation supply. If soil base cations are deficient, the catchment will have a lesser ability to buffer strong acids entering the ecosystem. Additional soil acidity might also release additional previously soil-bound Al.

Results of this study can be useful to inform management regarding locations at which habitats may be protected, effects on soil base cation reserves from timber harvesting may need to be mitigated, or fish stocking may be warranted. National Forests are recipients of acidic deposition that is transported long distances, and land managers may want to engage with air regulatory agencies to seek reductions in acid deposition. A land manager can inform the air regulatory agencies on the desired deposition to remain below (i.e. the CL) to achieve a desired soil or stream chemical condition. Though land managers do not control the amount of acidic deposition, they can reduce the amount of nutrient base cations removed through timber harvesting in order to protect the stream ANC. In this analysis, for all catchments outside of wildernesses, inventory roadless areas, and some other catchments that will likely not be subjected to timber harvest, it is assumed that harvesting will occur sometime in the future. For critical loads modeling with SSWC and SMB (and also for MAGIC modeling) the B_{cup} values used represent annual uptake of nutrient base cations following 65% removal of the tree trunks (bark and boles) with a timber harvest. Harvest rates below 65% would protect for higher stream ANC. McDonnell et al. (2013) used MAGIC to show that soil BS and the stream ANC were expected to increase for at least half of the study sites if 45% or less of the bark and boles were removed from a catchment. Despite having little control over acid deposition, land managers do have options to protect or improve base cation reserves and consequently the health of aquatic and terrestrial ecosystems.

There may be situations for which land managers will need to remove timber from acid-sensitive catchments. This might result, for example, from an effort to convert the catchment to native shortleaf pine or improve habitat for one or more wildlife species. A manager may want to reintroduce extirpated native brook trout to streams that have other good habitat characteristics. For these situations, the land manager could apply lime to the stream or soil. Placing lime adjacent to headwater (first order) streams on the George Washington National Forest resulted in an increase in stream pH and ANC, and a decrease in the concentration of Al_i . After liming, brook trout reintroduced into the stream reproduced annually for the three years of observations (Hudy et al. 2000). Water quality also improved following catchment liming, which included application of wollastonite ($CaSiO_3$) to the soil and streams. The application rate was intended to increase the BS from 10% to 19% in the upper mineral soil. Base saturation increased significantly, and the area with BS less than 10% decreased substantially. Following treatment, soil exchangeable calcium and pH increased, and soil exchangeable Al decreased. There was an increase in soil water pH and ANC (Cho et al. 2010) and stream response was immediate (Peters et al. 2004). Following an application of dolomitic lime and wildfire, Elliott et al. (2013) reported BS = 19%, compared to the untreated and non-burned areas with BS of 4%. The benefits of liming in that study were short-lived, however, likely because of a low liming application rate. A liming study conducted by Long et al. (2015) applied 20 times more dolomitic lime than Elliott et al. (2013). The benefits of the higher application rate by Long et al. (2015) were still present after 21 years. Sugar maple foliage showed elevated concentrations of Ca and Mg and soil exchangeable Ca and Mg in both shallow and deep soil horizons also increased. Eight years after treatment, reductions in soil exchangeable Al were also observed. In the soil water, there were increases in Ca, Mg, and pH, and a decrease in Al. The authors

concluded that after 15 years, most or all of the lime application had dissolved and incorporated into the soil exchange system and vegetation, with some leaching from the soils (Long et al. 2015). In addition to liming, land managers may consider limiting the amount of base cations removed from sensitive catchments through timber harvesting.

5 CONCLUSIONS

In this study, stream water ANC and soil BS at MAGIC-modeled sties showed decreasing trends from year 1860 to ambient (2016) conditions. Most sites showed marginal more recent ANC recovery under the base scenario, whereas BS continued to decline for the sites that had pre-industrial BS < 10%. Due to the effects of anthropogenic S and N deposition, there were 70 streams (40% of modeled streams) with ANC below 30 $\mu\text{eq/L}$ by the year 2016. Under the Base Case scenario, 24 streams were able to recover to ANC above 30 $\mu\text{eq/L}$ and the Regional Haze scenario was expected to recover an additional 13 streams to greater than 30 $\mu\text{eq/L}$. Thirty-three streams were expected to remain below ANC = 30 $\mu\text{eq/L}$, even with the additional deposition reductions simulated with the Regional Haze Rule scenario. Soil BS was low (< 12%) for about one-third ($n = 65$) of the modeled sites in the year 1860, increasing to one-half ($n = 89$) under ambient conditions.

It was determined that approximately 17% of the MAGIC modeled streams ($n = 30$) were not able to attain ANC of 30 $\mu\text{eq/L}$ by year 2100, even if S deposition was reduced to zero. These streams can be considered “can’t get there from here” with only S deposition reductions. The proportion of modeled streams that can’t get there from here by the year 2100 increased to 44% ($n = 77$); 19 had pre- industrial ANC < 50 $\mu\text{eq/L}$. The simulations suggested that only 5 of these 19 streams would be able to recover to ANC=30 $\mu\text{eq/L}$ by the year 2100.

Given that some streams were not able to recover to their pre-industrial ANC level, the TLs based on the criterion of pre-industrial ANC minus 10 $\mu\text{eq/L}$ can provide an indication of whether any of the streams that are “can’t get there from here” for ANC = 30 $\mu\text{eq/L}$ might come close to attaining this target. However, the modeling suggested that none of these 14 streams would recover to within 10 $\mu\text{eq/L}$ of pre-industrial ANC. This set of streams represents the most acid-sensitive watersheds among the modeled set, half of which are located on the Jefferson NF and the other half are located among the Cherokee NF, Pisgah NF, Nantahala NF, and Otter Creek/Dolly Sods Wilderness Area locations.

One-quarter of the MAGIC-modeled streams ($n = 44$) were in exceedance of the TL to attain ANC = 30 $\mu\text{eq/L}$ by the year 2100. This number nearly doubled ($n = 86$) based on TLs and deposition to attain ANC = 50 $\mu\text{eq/L}$ by the same year.

Regional predictions of recent stream ANC were heterogeneous among and within the NFs, with streams predicted to have ANC < 100 $\mu\text{eq/L}$ interspersed with those expected to have ANC > 100 $\mu\text{eq/L}$. The Monongahela NF had the greatest percent area with low (< 30 $\mu\text{eq/L}$) ANC at about 20%.

Critical loads of S deposition derived from the SSWC model for the protection of aquatic biota were relatively low for many areas located within National Forest boundaries. More than one-quarter of the streams in the Nantahala NF were expected to be in exceedance of the aquatic CL for attaining ANC = 50 $\mu\text{eq/L}$ or greater. Areas of exceedance tended to have relatively low weathering rates, in addition to being subjected to elevated S deposition.

Critical loads for the protection of terrestrial biota derived from the SMB model were generally higher than those determined for aquatic systems. Most of the terrestrial CLs < 50 $\text{meq/m}^2/\text{yr}$ were found on the Jefferson NF.

Results of this study can be useful to inform management regarding locations at which habitats may be protected, timber harvesting may need to be mitigated, or fish stocking may be warranted. Land managers may want to engage with air regulatory agencies to seek reductions in acid deposition. Reducing the amount of nutrient base cations removed by timber harvesting or through watershed liming could also be used as a tool for protecting associated stream ANC in acid-sensitive areas. Mitigation of forest harvesting in sensitive catchments exceeding the CL in this study may allow for maintaining, or achieving, stream ANC at levels generally supportive of aquatic biota.

6 REFERENCES CITED

- Adams, M.B., J.A. Burger, A.B. Jenkins, and L. Zelazny. 2000. Impact of harvesting and atmospheric pollution on nutrient depletion of eastern U.S. hardwood forests. *For. Ecol. Manage.* 138:301-319.
- Baker, J.P., J. Van Sickle, C.J. Gagen, D.R. DeWalle, W.E. Sharpe, R.F. Carline, B.P. Baldigo, P.S. Murdoch, D.W. Bath, W.A. Kretser, H.A. Simonin, and P.J. Wigington, Jr. 1996. Episodic acidification of small streams in the northeastern United States: effects on fish populations. *Ecol. Appl.* 6(2):423-437.
- Baker, L.A., J.M. Eilers, R.B. Cook, P.R. Kaufmann, and A.T. Herlihy. 1991. Current water chemistry and biogeochemical processes in case study regions: Intercomparison and synthesis. *In* D.F. Charles (Ed.) *Acidic Deposition and Aquatic Ecosystems: Regional Case Studies*. Springer-Verlag, Inc., New York. pp. 567-614.
- Baldigo, B.P., G.B. Lawrence, and H.A. Simonin. 2007. Persistent mortality of brook trout in episodically acidified streams of the southwestern Adirondack Mountains, New York. *Trans. Am. Fish. Soc.* 136:121-134.
- Baldigo, B.P., M.A. Kulp, and J.S. Schwartz. 2018. Relationships between indicators of acid-base chemistry and fish assemblages in streams of the Great Smoky Mountains National Park. *Ecol. Indic.* 88:465-484. <https://doi.org/10.1016/j.ecolind.2018.01.021>.
- Beven, K.J. and M.J. Kirkby. 1979. A physically based, variable contributing area model of basin hydrology / Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant. *Hydrological Sciences Bulletin* 24:43-69. 10.1080/02626667909491834.
- Bulger, A.J., B.J. Cosby, and J.R. Webb. 2000. Current, reconstructed past, and projected future status of brook trout (*Salvelinus fontinalis*) streams in Virginia. *Can. J. Fish. Aquat. Sci.* 57(7):1515-1523.
- Bulger, A.J., B.J. Cosby, C.A. Dolloff, K.N. Eshleman, J.R. Webb, and J.N. Galloway. 1999. SNP:FISH, Shenandoah National Park: Fish in Sensitive Habitats. Project Final Report to National Park Service. University of Virginia, Charlottesville, VA.
- Burrough, P.A. and R.A. McDonnell. 1998. *Principles of Geographical Information Systems*, 2nd Edition. Oxford Univ. Press, New York. 333 pp.
- Cho, Y., C.T. Driscoll, C.E. Johnson, and T.G. Siccama. 2010. Chemical changes in soil and soil solution after calcium silicate addition to a northern hardwood forest. *Biogeochemistry* 100(1):3-20. 10.1007/s10533-009-9397-6.
- Cosby, B.J., S.A. Norton, and J.S. Kahl. 1996. Using a paired catchment manipulation experiment to evaluate a catchment-scale biogeochemical model. *Sci. Total Environ.* 183:49-66.
- Cosby, B.J., G.M. Hornberger, J.N. Galloway, and R.F. Wright. 1985a. Time scales of catchment acidification: a quantitative model for estimating freshwater acidification. *Environ. Sci. Technol.* 19:1144-1149.
- Cosby, B.J., G.M. Hornberger, J.N. Galloway, and R.F. Wright. 1985b. Modelling the effects of acid deposition: assessment of a lumped parameter model of soil water and streamwater chemistry. *Water Resour. Res.* 21(1):51-63.
- Cosby, B.J., G.M. Hornberger, P.F. Ryan, and D.M. Wolock. 1989. MAGIC/DDRP Final Report. U.S. Environmental Protection Agency, Corvallis, OR.
- Cosby, B.J., R.C. Ferrier, A. Jenkins, and R.F. Wright. 2001. Modeling the effects of acid deposition: refinements, adjustments and inclusion of nitrogen dynamics in the MAGIC model. *Hydrol. Earth Syst. Sci.* 5(3):499-517.

- Cosby, B.J., J.R. Webb, J.N. Galloway, and F.A. Deviney. 2006. Acidic Deposition Impacts on Natural Resources in Shenandoah National Park. NPS/NER/NRTR-2006/066. U.S. Department of the Interior, National Park Service, Northeast Region, Philadelphia, PA.
- Cosby, B.J., A. Jenkins, R.C. Ferrier, J.D. Miller, and T.A.B. Walker. 1990. Modelling stream acidification in afforested catchments: long-term reconstructions at two sites in central Scotland. *J. Hydrol.* 120:143-162.
- Cronan, C.S. and D.F. Grigal. 1995. Use of calcium/aluminum ratios as indicators of stress in forest ecosystems. *J. Environ. Qual.* 24:209-226.
- Elliott, K.J., J.D. Knoepp, J.M. Vose, and W.A. Jackson. 2013. Interacting effects of wildfire severity and liming on nutrient cycling in a southern Appalachian wilderness area. *Plant and Soil*. DOI 10.1007/s11104-012-1416-z. DOI: 10.1007/s11104-012-1416-z.
- Galloway, J.N., S.A. Norton, and M.R. Church. 1983. Freshwater acidification from atmospheric deposition of sulfuric acid: a conceptual model. *Environ. Sci. Technol.* 17:541A-545A.
- Grimm, J. and J. Lynch. 2004. Enhanced Wet Deposition Estimates using Modeled Precipitation Inputs. *Environ. Monitor. Assess.* 90(1-3):243-268.
10.1023/B:EMAS.0000003592.56006.a0.
- Grimm, J.W. and J.A. Lynch. 1997. Enhanced Wet Deposition Estimates Using Modeled Precipitation Inputs. Final Report to U.S. Forest Service under Cooperative Agreement #23-721. Environmental Resources Research Institute, The Pennsylvania State University, University Park, PA.
- Hargrove, W.W. and F.M. Hoffman. 2004. A Flux Atlas for Representativeness and Statistical Extrapolation of the AmeriFlux Network. Technical Memorandum ORNL/TM-2004/112. Oak Ridge National Laboratory, Oak Ridge, TN.
- Henriksen, A. and M. Posch. 2001. Steady-state models for calculating critical loads of acidity for surface waters. *Water Air Soil Pollut: Focus* 1(1-2):375-398.
- Hornberger, G.M., B.J. Cosby, and R.F. Wright. 1989. Historical reconstructions and future forecasts of regional surface water acidification in southernmost Norway. *Water Resour. Res.* 25:2009-2018.
- Hudy, M., D.M. Downey, and D.W. Bowman. 2000. Successful restoration of an acidified native brook trout stream through mitigation with limestone sand. *N. Am. J. Fish. Manage.* 20:453-466.
- Jenkins, A., P.G. Whitehead, T.J. Musgrove, and B.J. Cosby. 1990a. A regional model of acidification in Wales. *J. Hydrol.* 116:403-416.
- Jenkins, A., P.G. Whitehead, B.J. Cosby, R.C. Ferrier, and D.J. Waters. 1990b. Modelling long term acidification: a comparison with diatom reconstructions and the implications for reversibility. *Phil. Trans. R. Soc. Lond.* 327:435-440.
- Jenkins, A., B.J. Cosby, R.C. Ferrier, T.A.B. Walker, and J.D. Miller. 1990c. Modelling stream acidification in afforested catchments: an assessment of the relative effects of acid deposition and afforestation. *J. Hydrol.* 120:163-181.
- Jenson, S.K. and J.O. Domingue. 1988. Extracting topographic structure from digital elevation data for geographic information system analysis. *Photogramm Eng Remote Sensing* 54(11):1593-1600.
- Lawrence, G.B., T.J. Sullivan, D.A. Burns, S.A. Bailey, B.J. Cosby, M. Dovciak, H.A. Ewing, T.C. McDonnell, R. Minocha, J. Quant, K.C. Rice, J. Siemion, and K. Weathers. 2015. Acidic Deposition along the Appalachian Trail Corridor and its Effects on Acid-Sensitive Terrestrial and Aquatic Resources. Results of the Appalachian Trail MEGA-Transect

- Atmospheric Deposition Effects Study. Natural Resource Report
NPS/NRSS/ARD/NRR—2015/996. National Park Service, Fort Collins, CO.
- Li, H. and S.G. McNulty. 2007. Uncertainty analysis on simple mass balance model to calculate critical loads for soil acidity. *Environ. Pollut.* 149:315-326.
- Long, R.P., S.W. Bailey, S.B. Horsley, T.J. Hall, B.R. Swistock, and D.R. DeWalle. 2015. Long-Term Effects of Forest Liming on Soil, Soil Leachate, and Foliage Chemistry in Northern Pennsylvania. *Soil Sci. Soc. Am. J.* 79(4):1223-1236. 10.2136/sssaj2014.11.0465.
- McCabe, G.J. and D.M. Wolock. 2011. Independent effects of temperature and precipitation on modeled runoff in the conterminous United States. *Water Resour. Res.* 47(11):W11522. 10.1029/2011WR010630.
- McDonnell, T.C., B.J. Cosby, and T.J. Sullivan. 2012. Regionalization of soil base cation weathering for evaluating stream water acidification in the Appalachian Mountains, USA. *Environ. Pollut.* 162:338-344.
- McDonnell, T.C., T.J. Sullivan, B.J. Cosby, W.A. Jackson, and K. Elliott. 2013. Effects of climate, land management, and sulfur deposition on soil base cation supply in national forests of the Southern Appalachian Mountains. *Water Air Soil Pollut.* 224:1733. DOI 10.1007/s11270-013-1733-8.
- McDonnell, T.C., T.J. Sullivan, P.F. Hessburg, K.M. Reynolds, N.A. Povak, B.J. Cosby, W. Jackson, and R.B. Salter. 2014. Steady-state sulfur critical loads and exceedances for protection of aquatic ecosystems in the U.S. southern Appalachian Mountains. *J. Environ. Manage.* 146:407-419. <http://dx.doi.org/10.1016/j.jenvman.2014.07.019>.
- McDonnell, T.C., M.R. Sloat, T.J. Sullivan, C.A. Dolloff, P.F. Hessburg, N.A. Povak, W.A. Jackson, and C. Sams. 2015. Downstream Warming and Headwater Acidity May Diminish Coldwater Habitat in Southern Appalachian Mountain Streams. *PLoS ONE* 10(8):e0134757. 10.1371/journal.pone.0134757.
- McNulty, S.G. and J.L. Boggs. 2010. A conceptual framework: Redefining forest soil's critical acid loads under a changing climate. *Environ. Pollut.* 158:2053-2058.
- McNulty, S.G., E.C. Cohen, J.A.M. Myers, T.J. Sullivan, and H. Li. 2007. Estimates of critical acid loads and exceedances for forest soils across the conterminous United States. *Environ. Pollut.* 149:281-292.
- National Acid Precipitation Assessment Program. 1991. Integrated Assessment Report. National Acid Precipitation Assessment Program, Washington, DC.
- Nilsson, J. and P. Grennfelt. 1988. Critical Loads for Sulphur and Nitrogen. *Miljørapport* 1988:15. Nordic Council of Ministers, Copenhagen.
- Norton, S.A., R.F. Wright, J.S. Kahl, and J.P. Scofield. 1992. The MAGIC simulation of surface water acidification at, and first year results from, the Bear Brook Watershed Manipulation, Maine, USA. *Environ. Pollut.* 77:279-286.
- Peters, S.C., J.D. Blum, C.T. Driscoll, and G.E. Likens. 2004. Dissolution of wollastonite during the experimental manipulation of Hubbard Brook Watershed I. *Biogeochemistry* 67:309-329.
- Posch, M., P.A.M. DeSmet, J.P. Hettelingh, and R.J. Downing. 2001. Calculation and mapping of critical thresholds in Europe. Status report 2001. Coordination Center for Effects, National Institute of Public Health and the Environment (RIVM), Bilthoven, The Netherlands.

- Povak, N.A., P.F. Hessburg, K.M. Reynolds, T.J. Sullivan, T.C. McDonnell, and R.B. Salter. 2013. Machine learning and hurdle models for improving regional predictions of stream water acid neutralizing capacity. *Water Resour. Res.* 49. 10.1002/wrcr.20308.
- Povak, N.A., P.F. Hessburg, T.C. McDonnell, K.M. Reynolds, T.J. Sullivan, R.B. Salter, and B.J. Cosby. 2014. Machine learning and linear regression models to predict catchment-level base cation weathering rates across the southern Appalachian Mountain region, USA. *Water Resour. Res.* 50(4):2798-2814. DOI: 10.1002/2013WR014203.
- Reynolds, K.M., P.F. Hessburg, T. Sullivan, N. Povak, T. McDonnell, B. Cosby, and W. Jackson. 2012. Spatial decision support for assessing impacts of atmospheric sulfur deposition on aquatic ecosystems in the Southern Appalachian Region. *In Proc. of the 45th Hawaiian International Conference on System Sciences*, 4-7 January 2012, Maui, Hawaii
- Rice, K.C., T.M. Scanlon, J.A. Lynch, and B.J. Cosby. 2014. Decreased atmospheric sulfur deposition across the southeastern U.S.: When will watersheds release stored sulfate? *Environ. Sci. Technol.* 48(17):10071-10078. 10.1021/es501579s.
- Robison, A.L., T.M. Scanlon, B.J. Cosby, J.R. Webb, and J.N. Galloway. 2013. Roles of sulfate adsorption and base cation supply in controlling the chemical response of streams of western Virginia to reduced acid deposition. *Biogeochemistry* 116(1):119-130. 10.1007/s10533-013-9921-6.
- Schwede, D.B. and G.G. Lear. 2014. A novel hybrid approach for estimating total deposition in the United States. *Atmos. Environ.* 92:207-220.
<http://dx.doi.org/10.1016/j.atmosenv.2014.04.008>.
- Scott, J.M., F. Davis, B. Csuti, R. Noss, B. Butterfield, C. Groves, H. Anderson, S. Caicco, F. D'Ercchia, T.C. Edwards, Jr., J. Ulliman, and R.G. Wright. 1993. Gap analysis: A geographic approach to protection of biological diversity. *Wildlife Monographs No. 123* (January 1993).
- Shannon, J.D. 1998. Calculations of trends from 1900 through 1990 for sulfur and NO_x-N deposition concentrations of sulfate and nitrate in precipitation, and atmospheric concentrations of SO_x and NO_x species over the southern Appalachians. Report to SAMI.
- Smith, E.P. and R. Voshell. 2013. Analysis of Benthic Metrics in GWJ. Virginia Tech, Blacksburg, VA.
- Sullivan, T.J. 2017. Air Pollution and Its Impacts on U.S. National Parks. CRC Press, Boca Raton, FL. 638 pp.
- Sullivan, T.J. and B.J. Cosby. 1998. Modeling the concentration of aluminium in surface waters. *Water Air Soil Pollut.* 105:643-659.
- Sullivan, T.J., D.W. Johnson, and R. Munson. 2002a. Assessment of Effects of Acid Deposition on Forest Resources in the Southern Appalachian Mountains. Report prepared for the Southern Appalachian Mountains Initiative (SAMI). E&S Environmental Chemistry, Inc., Corvallis, OR.
- Sullivan, T.J., B.J. Cosby, and W.A. Jackson. 2011a. Target loads of atmospheric sulfur deposition for the protection and recovery of acid-sensitive streams in the Southern Blue Ridge Province. *J. Environ. Manage.* 92(11):2953-2960. 10.1016/j.jenvman.2011.07.014.
- Sullivan, T.J., B.J. Cosby, K.U. Snyder, A.T. Herlihy, and B. Jackson. 2007. Model-Based Assessment of the Effects of Acidic Deposition on Sensitive Watershed Resources in the National Forests of North Carolina, Tennessee, and South Carolina. Final report prepared

- for USDA Forest Service, Asheville, NC. E&S Environmental Chemistry, Inc., Corvallis, OR.
- Sullivan, T.J., B.J. Cosby, C.T. Driscoll, T.C. McDonnell, and A.T. Herlihy. 2011b. Target loads of atmospheric sulfur deposition to protect terrestrial resources in the Adirondack Mountains, New York against biological impacts caused by soil acidification. *J. Environ. Stud. Sci.* 1(4):301-314.
- Sullivan, T.J., B.J. Cosby, B. Jackson, K.U. Snyder, and A.T. Herlihy. 2011c. Acidification and prognosis for future recovery of acid-sensitive streams in the Southern Blue Ridge Province. *Water Air Soil Pollut.* 219:11-26.
- Sullivan, T.J., B.J. Cosby, J.R. Webb, K.U. Snyder, A.T. Herlihy, A.J. Bulger, E.H. Gilbert, and D. Moore. 2002b. Assessment of the Effects of Acidic Deposition on Aquatic Resources in the Southern Appalachian Mountains. Report prepared for the Southern Appalachian Mountains Initiative (SAMI). E&S Environmental Chemistry, Inc., Corvallis, OR.
- Sullivan, T.J., B.J. Cosby, A.T. Herlihy, J.R. Webb, A.J. Bulger, K.U. Snyder, P. Brewer, E.H. Gilbert, and D.L. Moore. 2004. Regional model projections of future effects of sulfur and nitrogen deposition on streams in the southern Appalachian Mountains. *Water Resour. Res.* 40: W02101. doi:10.1029/2003WR001998.
- Sullivan, T.J., C.T. Driscoll, C.M. Beier, D. Burtraw, I.J. Fernandez, J.N. Galloway, D.A. Gay, C.L. Goodale, G.E. Likens, G.M. Lovett, and S.A. Watmough. 2018. Air pollution success stories in the United States: The value of long-term observations. *Environ. Sci. Policy* 84:69-73. <https://doi.org/10.1016/j.envsci.2018.02.016>.
- Sullivan, T.J., C.T. Driscoll, B.J. Cosby, I.J. Fernandez, A.T. Herlihy, J. Zhai, R. Stemberger, K.U. Snyder, J.W. Sutherland, S.A. Nierzwicki-Bauer, C.W. Boylen, T.C. McDonnell, and N.A. Nowicki. 2006. Assessment of the Extent to Which Intensively-Studied Lakes Are Representative of the Adirondack Mountain Region. Final Report 06-17. New York State Energy Research and Development Authority, Albany, NY.
- Tomlinson, G.H. 1990. Effects of Acid Deposition on the Forests of Europe and North America. CRC Press, Boca Raton, FL. 281 pp.
- U.S. Environmental Protection Agency. 2008. Integrated Science Assessment for Oxides of Nitrogen and Sulfur -- Ecological Criteria. EPA/600/R-08/082F. National Center for Environmental Assessment, Office of Research and Development, Research Triangle Park, NC.
- U.S. Environmental Protection Agency. 2009. Risk and Exposure Assessment for Review of the Secondary National Ambient Air Quality Standards for Oxides of Nitrogen and Oxides of Sulfur: Final. EPA-452/R-09-008a. Office of Air Quality Planning and Standards, Health and Environmental Impacts Division, Research Triangle Park, NC.
- U.S. Environmental Protection Agency. 2016. SSURGO-STATSGO Raster Datasets. Retrieved December 27, 2016 from enviroatlas.epa.gov/enviroatlas.
- Watmough, S.A., J. Aherne, and P.J. Dillion. 2004. Critical Loads Ontario: Relating Exceedance of the Critical Loads with Biological Effects at Ontario Forests. Report 2. Environmental and Resource Studies, Trent University, Ontario. 22 pp.
- Wolock, D.M. 2003. Base-flow index grid for the conterminous United States. Available at: water.usgs.gov/GIS/metadata/usgswrd/ [accessed January 3, 2014].
- Wright, R.F., B.J. Cosby, M.B. Flaten, and J.O. Reuss. 1990. Evaluation of an acidification model with data from manipulated catchments in Norway. *Nature* 343:53-55.

- Wright, R.F., B.J. Cosby, R.C. Ferrier, A. Jenkins, A.J. Bulger, and R. Harriman. 1994. Changes in the acidification of lochs in Galloway, southwestern Scotland, 1979-1988: the MAGIC model used to evaluate the role of afforestation, calculate critical loads, and predict fish status. *J. Hydrol.* 161:257-285.
- Yarnell, S.L. 1998. The Southern Appalachians: a history of the landscape. General Technical Report SRS-18. USDA Forest Service, Southern Research Station, Asheville, NC.
Available at: <http://www.srs.fs.usda.gov/pubs/331>.

APPENDICES

Appendix 1. Pre-Industrial Base Cation Cycling

Land managers can benefit from understanding how nutrient base cations (Ca + Mg + K) were cycled through forested catchments prior to European settlement and the onset of elevated acidic deposition. These nutrients are essential to support healthy and productive vegetation and terrestrial and aquatic organisms. For example, calcium is primary cell wall component of vegetation and provides support for vertebrates and invertebrates.

The main source of base cations to surface waters in an undisturbed watershed is from weathering of rock fragments in the soil by carbonic and organic acids; a smaller amount is the result of dust deposited from the atmosphere to the land surface. Carbon dioxide from the atmosphere produces carbonic acid, but the main source of carbonic acid is a by-product of respiration by roots and other soil organisms. Carbonic and organic acids are largely responsible for the continuous breakdown of rock fragments.

Prior to European settlement, the flux of SO_4^{2-} , alkalinity, and base cations in soil and drainage water were generally constant through time (Galloway et al. 1983). Soil base cation reserves remained relatively constant due to an established equilibrium between base cation inputs from weathering and windblown soil and outputs from leaching to surface waters. Continuous plant growth occurred because base cations taken up by vegetation were returned to the soil and made available for subsequent uptake through decomposition of fallen plant material (Tomlinson 1990). The relative abundance of base cations in watershed soils and streams varied across the forests because of different bedrock geology from which various soil types were formed (Sullivan et al. 2004). For example, soils developed on metamorphosed granitic rocks contained far less base cation content than soils derived from limestone.

Reductions in soil exchangeable base cation concentrations occurred following European settlement. Starting in the late 1800s, soil base cation pools were reduced due to removal in one

or more timber harvests, soil erosion due to poor logging practices, and wildfires (Yarnell 1998). The removal of tree trunks and loss of soil to erosion removed base cations from the system, disrupting the steady state dynamic and causing soils to become more acidic. Beginning with the Industrial Revolution, forests experienced additional acidification from S and N compounds deposited from industrial pollution which increased base cation leaching. This elevated acidic deposition and unsustainable base cation leaching peaked in 1980s and continues to this day.

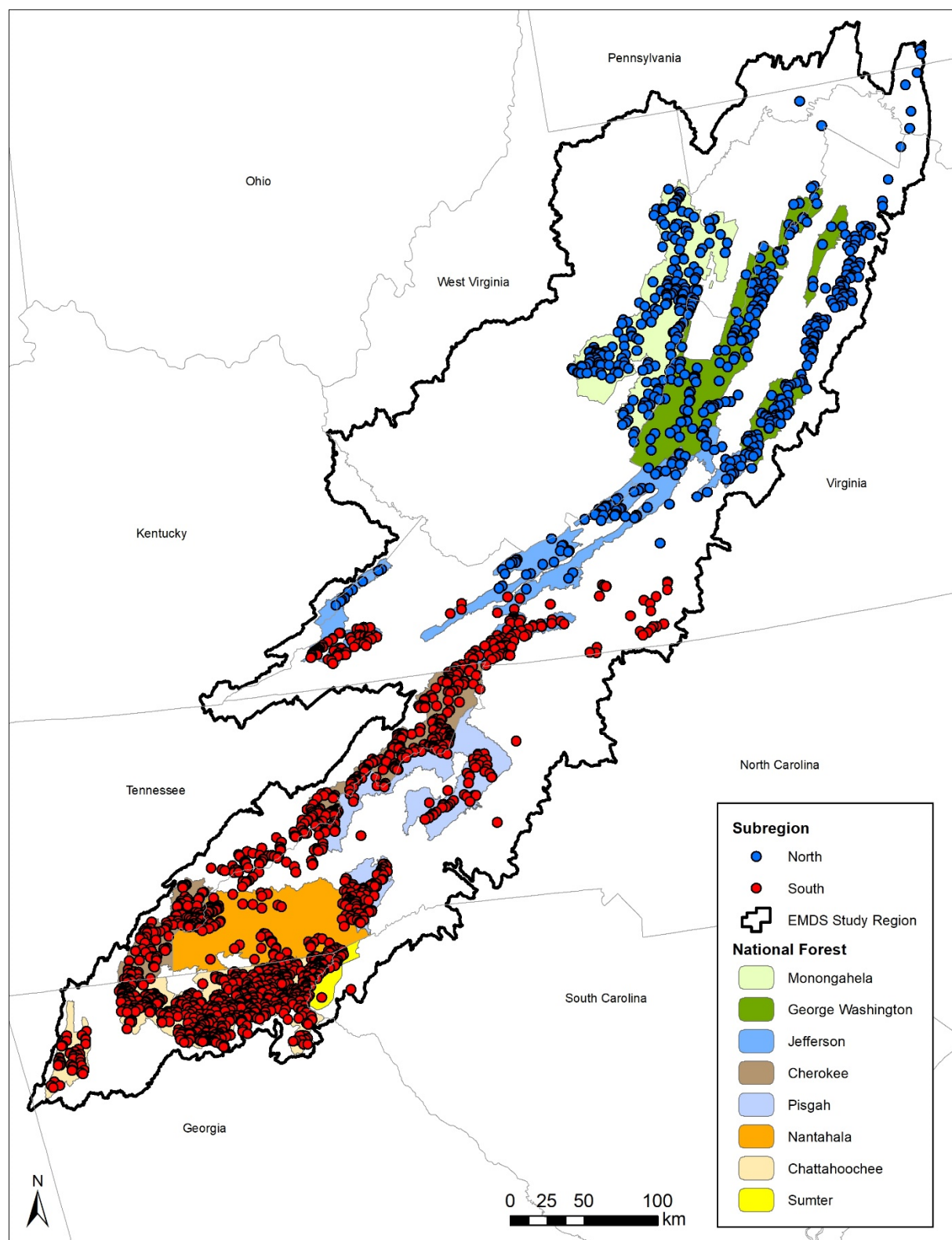
Appendix 2. Candidate Predictor Variables for Regression Modeling

Variable ID	Description	Factor	Units	Citation
lat	Latitude	None	decimal degrees	Derived
lon	Longitude	None	decimal degrees	Derived
elev	Elevation	None	m	NHDPlus; http://www.horizon-systems.com/NHDPlus/NHDPlusV2_home.php
fac	Flow accumulation (watershed area)	900	m ²	Jenson and Domingue (1988)
BC _{w,FB}	Estimate of base cation weathering derived from flux balance: BCstream + BCup - BCdep	None	meq x m ² x yr ⁻¹	McCabe and Wolock (2011); McNulty et al. (2007); Grimm and Lynch (2004); Baker et al. (1991)
slope	Land slope	None	degree	Burrough and McDonnell (1998)
twi	Topographic wetness index	None	unitless	Beven and Kirkby (1979)
tavgann	30-year normal (1981 – 2000) average annual temperature	None	celsius	PRISM; http://prism.oregonstate.edu/
pptann	30-year normal (1981 – 2000) average annual precipitation	None	mm	PRISM; http://prism.oregonstate.edu/
runoff	Water balance runoff	None	m x yr ⁻¹	McCabe and Wolock (2011)
bfi	Base flow index: Ratio of base flow to total flow	None	unitless	Wolock (2003)
draindens	Ratio of stream length to watershed area	None	m ²	NHDPlus; http://www.horizon-systems.com/NHDPlus/NHDPlusV2_home.php
sdep0002	Total (wet + dry + occult) sulfur deposition	None	meq x m ² x yr ⁻¹	Grimm and Lynch (2004), TDEP, Shannon
conmix	Percent contributing area in conifer (1) + mixed (0.5) cover (weighted by # in parentheses)	None	percent	NLCD; https://www.mrlc.gov/
decmix	Percent contributing area in deciduous (1) + mixed (0.5) cover (weighted by # in parentheses)	None	percent	NLCD; https://www.mrlc.gov/
litharg	Percent contributing area in argillic lithology	100	percent	USGS; http://mrdata.usgs.gov/geology/state
lithcar	Percent contributing area in carbonaceous lithology	100	percent	USGS; http://mrdata.usgs.gov/geology/state
lithfel	Percent contributing area in felsic lithology	100	percent	USGS; http://mrdata.usgs.gov/geology/state
lithmaf	Percent contributing area in mafic lithology	100	percent	USGS; http://mrdata.usgs.gov/geology/state
lithsil	Percent contributing area in siliceous lithology	100	percent	USGS; http://mrdata.usgs.gov/geology/state

Variable ID	Description	Factor	Units	Citation
soilph	Soil pH	None	pH units	N. Bliss, USGS contractor, pers. comm., April 14, 2017
ecec	Cation exchange capacity	None	meq x 100g ⁻¹	N. Bliss, USGS contractor, pers. comm., April 14, 2017
deprz	Depth of rooting zone	None	m	N. Bliss, USGS contractor, pers. comm., April 14, 2017
db2mm	Bulk density (fine earth fraction)	None	g x cm ⁻³	N. Bliss, USGS contractor, pers. comm., April 14, 2017
sand	Soil percent sand	100	percent	N. Bliss, USGS contractor, pers. comm., April 14, 2017
clay	Soil percent clay	100	percent	N. Bliss, USGS contractor, pers. comm., April 14, 2017
hyda	Percentage of map unit with hydrologic group A	None	percent	U.S. EPA (2016)
hydb	Percentage of map unit with hydrologic group B	None	percent	U.S. EPA (2016)
hydc	Percentage of map unit with hydrologic group C	None	percent	U.S. EPA (2016)
hydd	Percentage of map unit with hydrologic group D	None	percent	U.S. EPA (2016)
nitronew	Mean soil Kjeldahl nitrogen to 50 cm depth	None	kg N x ha ⁻¹	Hargrove and Hoffman (2004)
omnew	Mean soil organic matter to 50 cm depth	0.01	kg OM x ha ⁻¹	Hargrove and Hoffman (2004)
pered	Percentage of map unit Excessively Drained	None	percent	U.S. EPA (2016)
persed	Percentage of map unit Somewhat Excessively Drained	None	percent	U.S. EPA (2016)
perwd	Percentage of map unit Well Drained	None	percent	U.S. EPA (2016)
permwd	Percentage of map unit Moderately Well Drained	None	percent	U.S. EPA (2016)
perspd	Percentage of map unit Somewhat Poorly Drained	None	percent	U.S. EPA (2016)
perpd	Percentage of map unit Poorly Drained	None	percent	U.S. EPA (2016)
pervpd	Percentage of map unit Very Poorly Drained	None	percent	U.S. EPA (2016)
ab90grow	Mean number of days above 32.2C during the local growing season	0.01	days	Hargrove and Hoffman (2004)
diff95grow	Mean 95th Percentile of maximum diurnal surface temperature difference during the local growing season	0.02	kelvin	Hargrove and Hoffman (2004)
diff95ng	Mean 95th Percentile of maximum diurnal surface temperature difference during the local non-growing season	0.02	kelvin	Hargrove and Hoffman (2004)
gppng	Mean gross primary production (GPP)	0.0001	(kg C x m ² x 8 days) x days	Hargrove and Hoffman (2004)

Variable ID	Description	Factor	Units	Citation
	integrated over the local non-growing season			
npdaymax	Mean penultimate maximum days without precipitation (<0.3cm) while > 10C	None	days	Hargrove and Hoffman (2004)
pdaymax	Mean penultimate maximum days with precipitation (>0.3cm) while > 10C	None	days	Hargrove and Hoffman (2004)
precipng	Mean precipitation sum during the local non-growing season	0.01	millimeters	Hargrove and Hoffman (2004)
vdcontday	Mean penultimate maximum consecutive days vpd > 750 pa while > 10C	None	days	Hargrove and Hoffman (2004)
vwdaymax	Mean penultimate maximum days vpd < 1000 pa while > 10C	None	days	Hargrove and Hoffman (2004)

Appendix 3. Water Chemistry Site Locations (North/South)



Appendix 4. MAGIC Modeled Acid Neutralizing Capacity (ANC) Scenario Results

Table A3-1. ANC (µeq/L) scenario results from MAGIC modeling for years 1860, 2016, and years 2060, 2100, and 2170 under the three future scenarios.

Site ID	Hindcast	Current	Base Case			Regional Haze			Regional Haze + Red N		
	1860	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
0819003359391	35.8	-14.1	-4.8	1.0	7.3	-2.1	7.0	16.6	-2.1	6.9	16.5
0819333365729	37.7	21.4	20.4	19.7	18.7	22.6	23.0	23.7	22.6	23.0	23.7
0819405365852	72.7	25.3	29.6	32.1	35.3	33.9	39.5	46.5	33.8	39.4	46.3
0819976365378	368.9	341.0	339.0	337.6	336.0	340.3	340.8	342.3	340.3	340.8	342.2
0820288361949	172.4	132.8	137.0	139.4	141.8	139.0	144.3	150.1	139.0	144.3	150.1
0820575365023	310.0	288.7	285.1	282.7	279.7	286.3	285.5	285.3	286.3	285.4	285.2
0820659362857	144.5	120.1	121.9	122.6	123.4	123.2	125.6	129.0	123.2	125.6	129.0
0821098362008	132.8	108.4	112.0	113.7	114.8	114.5	117.8	120.3	114.4	117.7	120.1
0821111362567	126.4	69.5	73.5	78.8	86.4	77.7	86.8	98.3	77.6	86.6	98.1
0821665364328	74.5	-1.8	14.1	22.2	30.9	19.2	32.0	45.4	19.1	31.9	45.3
0822058362619	99.6	26.6	53.4	62.7	70.3	58.0	71.3	82.7	57.9	71.3	82.7
0822102358016	58.4	27.3	28.3	29.4	31.1	30.7	33.9	38.5	30.6	33.8	38.3
0822122357913	58.1	26.6	28.6	30.4	33.0	31.0	34.9	40.2	30.9	34.8	40.0
0822144357431	67.1	35.6	33.4	32.0	30.4	35.5	36.7	39.2	35.4	36.7	39.2
0822446357370	59.9	24.3	25.9	27.9	30.8	29.0	33.4	39.2	28.8	33.2	39.1
0822486357318	52.6	17.5	18.3	19.1	20.7	21.2	24.5	29.4	21.1	24.3	29.2
0822632361472	86.0	30.9	49.7	57.1	63.3	52.9	63.6	72.8	52.9	63.6	72.8
0822811357260	58.0	33.0	32.8	32.7	32.7	35.0	36.7	39.2	34.9	36.6	39.1
0823970361827	189.5	177.2	172.7	170.2	168.6	173.1	171.6	172.5	173.1	171.6	172.5
0824227362028	140.0	62.0	89.9	102.5	112.8	93.4	109.9	123.9	93.4	109.9	123.9
0824312360996	73.9	14.9	33.3	42.1	50.1	36.7	48.9	60.1	36.7	48.9	60.1
0825384359725	168.1	146.1	141.9	139.4	137.2	144.8	144.6	145.7	144.7	144.4	145.4
0825869361157	114.7	84.7	86.8	87.1	86.7	92.9	94.9	96.7	92.4	94.4	96.0

Site ID	Hindcast	Current	Base Case			Regional Haze			Regional Haze + Red N		
	1860	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
0826140361316	223.1	146.9	171.2	180.8	188.8	174.9	188.3	200.6	174.8	188.2	200.5
0826540361058	115.0	47.0	77.9	85.2	89.3	84.3	95.9	103.5	84.1	95.8	103.3
0826728360724	48.2	31.6	34.9	37.1	39.6	35.7	39.1	42.9	35.8	39.2	43.0
0827495360190	132.9	88.4	93.8	94.3	94.3	105.1	108.4	109.8	104.2	107.3	108.7
0827728360271	174.0	97.2	124.1	136.0	145.6	127.7	143.3	156.8	127.7	143.4	156.8
0828146359682	170.8	61.0	100.0	108.3	114.1	108.4	124.0	136.9	108.4	124.0	136.8
0828261353375	55.4	40.4	40.2	40.3	40.7	40.9	42.1	44.3	41.0	42.2	44.4
0828670353323	44.3	18.1	17.9	18.0	18.6	19.1	21.3	24.7	19.1	21.3	24.7
0828817352953	71.6	21.5	40.7	45.9	49.3	46.4	54.7	60.4	46.2	54.4	60.1
0828920352772	65.7	39.5	42.4	44.5	47.4	44.2	48.1	52.9	44.1	48.0	52.8
0829067352780	69.7	24.6	46.4	51.0	53.9	50.7	58.6	63.6	50.6	58.6	63.6
0829079353270	49.4	28.7	29.9	31.3	33.7	31.0	33.8	38.0	31.0	33.8	38.0
0829160353045	71.3	44.0	45.7	48.1	51.6	47.0	51.2	57.1	47.0	51.2	57.1
0829184352865	71.2	21.9	46.0	52.5	56.1	50.3	60.0	65.9	50.2	59.9	65.8
0829194352886	53.9	14.6	32.2	36.7	39.2	36.8	43.8	48.1	36.6	43.6	47.9
0829321353099	59.6	39.0	41.1	43.2	46.2	42.1	45.6	50.3	42.1	45.6	50.3
0829630353646	77.2	44.9	44.3	43.8	43.6	48.2	49.9	52.7	47.9	49.6	52.4
0829670359613	102.6	90.9	90.3	89.9	89.5	90.8	91.3	92.2	90.8	91.3	92.2
0829674352788	64.7	48.0	48.0	48.4	49.2	49.1	50.6	53.1	49.0	50.5	53.0
0830494349738	88.4	77.9	77.1	76.4	75.6	77.6	77.7	78.1	77.6	77.7	78.0
0830849349820	83.7	74.4	73.5	72.8	71.9	74.0	74.0	74.4	74.1	74.2	74.6
0830946350205	57.9	48.5	48.0	47.7	47.4	48.4	48.7	49.5	48.4	48.7	49.5
0831036359106	132.3	43.7	56.8	66.9	78.7	61.9	77.8	95.2	62.1	78.0	95.4
0831139350208	68.3	53.6	54.6	55.8	57.4	55.4	57.5	60.5	55.4	57.5	60.4
0831205358440	652.3	622.8	620.5	619.2	617.9	621.9	622.4	624.1	621.9	622.4	624.0
0831285350075	83.2	73.5	72.7	72.3	71.8	73.1	73.3	74.0	73.1	73.3	74.0
0831579358839	70.1	32.1	34.4	36.0	38.1	36.3	40.7	46.3	36.3	40.7	46.3
0831907358024	559.8	482.9	486.8	495.6	507.6	491.0	505.3	523.1	490.9	505.1	522.8
0832042358247	65.6	50.4	48.4	47.5	46.8	49.0	49.3	50.6	49.0	49.3	50.6

Site ID	Hindcast	Current	Base Case			Regional Haze			Regional Haze + Red N		
	1860	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
0835047350176	39.4	29.1	28.8	28.7	28.7	29.4	30.0	31.0	29.4	29.9	31.0
0835085350173	48.5	37.9	37.6	37.4	37.2	38.1	38.7	39.6	38.1	38.6	39.6
0839239352738	63.0	37.9	38.7	39.3	40.6	40.9	43.2	46.7	40.8	43.1	46.6
0839262352702	57.7	42.1	41.8	41.7	41.7	42.7	43.7	45.3	42.7	43.7	45.3
0839336353542	109.1	101.1	100.1	99.3	98.2	100.5	100.3	100.2	100.5	100.3	100.2
0839358353530	56.8	31.3	32.6	33.6	34.9	34.6	37.4	40.9	34.5	37.3	40.9
0839517353661	54.6	38.7	38.5	38.4	38.3	39.1	40.2	41.9	39.1	40.2	41.9
0839594353679	69.5	44.0	48.6	52.0	55.9	50.2	55.3	61.0	50.2	55.3	61.0
0839829353633	54.6	23.3	35.5	39.7	42.6	38.7	44.9	49.2	38.6	44.8	49.1
0839976353481	37.3	7.5	14.6	18.0	21.0	19.1	24.2	28.8	18.9	24.0	28.5
0840110352961	56.0	20.5	29.2	33.7	37.7	33.6	40.1	45.9	33.3	39.8	45.6
0840139353542	68.1	26.1	37.0	41.7	45.7	42.8	49.9	56.0	42.5	49.6	55.6
0840233353666	117.1	32.3	53.0	61.5	68.4	65.8	78.9	89.7	64.9	78.0	88.7
0840303353155	46.3	-0.6	18.9	24.9	28.5	24.7	33.4	39.0	24.4	33.2	38.7
0840420353309	78.8	42.3	44.0	45.4	47.8	49.3	52.9	57.9	48.9	52.6	57.5
0840444353143	52.3	19.7	27.4	31.5	35.4	29.8	35.9	41.7	29.8	35.8	41.7
0840472353165	55.7	23.9	30.5	34.1	37.8	33.4	38.9	44.7	33.3	38.8	44.5
0840477353169	67.9	22.0	24.9	27.3	30.7	31.0	36.2	42.8	30.6	35.8	42.3
0840574353329	77.8	34.7	47.4	52.6	56.9	52.1	59.7	66.3	51.8	59.5	66.0
0840591352378	68.9	44.7	44.5	44.9	46.0	46.5	48.5	52.0	46.4	48.4	51.9
0840609353308	88.8	40.3	56.3	62.0	66.1	62.5	71.1	77.4	62.2	70.8	77.0
0840675353310	95.2	51.8	54.9	57.6	61.4	61.0	66.4	73.1	60.6	66.0	72.6
0840745352655	76.0	45.5	49.0	51.6	54.9	52.0	56.5	61.9	51.8	56.3	61.8
0840802352619	72.6	41.2	53.0	57.4	60.7	55.7	62.2	67.1	55.7	62.1	67.0
0840876355009	79.2	20.7	47.1	53.2	57.2	51.4	61.5	68.6	51.4	61.5	68.6
0840886352889	71.7	38.0	41.8	44.3	47.5	45.6	50.1	55.6	45.4	49.8	55.3
0840893352584	60.8	21.8	25.3	27.5	30.4	29.5	34.2	40.0	29.3	34.0	39.7
0840999353179	139.1	119.7	121.0	122.2	124.2	122.5	125.1	128.8	122.5	125.1	128.7
0841126353049	105.6	71.2	75.6	78.7	82.3	78.3	83.7	89.9	78.3	83.8	90.0

Site ID	Hindcast	Current	Base Case			Regional Haze			Regional Haze + Red N		
	1860	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
0841405354390	115.2	60.3	86.3	94.9	100.2	89.4	101.4	109.4	89.4	101.4	109.4
0841965353483	159.6	123.4	123.0	123.9	125.1	128.6	132.7	137.1	128.2	132.1	136.4
0842048352868	117.6	48.1	74.1	79.8	84.2	79.8	90.2	98.7	79.7	90.2	98.7
0843145352310	186.2	165.9	163.9	165.6	169.5	164.7	167.8	173.7	164.7	167.8	173.7
0843377352707	180.1	176.7	175.9	175.2	174.4	176.0	175.6	175.2	176.0	175.6	175.2
0843873352029	198.1	137.4	145.4	153.8	162.8	148.4	160.4	173.0	148.4	160.4	173.0
0844151352181	98.9	50.1	59.5	63.3	67.2	63.9	70.7	77.9	63.7	70.5	77.6
0844273352649	308.5	219.5	255.9	270.9	282.6	259.9	279.5	296.0	260.1	279.9	296.4
0844278351285	80.4	26.9	45.5	52.6	58.2	48.6	58.8	67.1	48.6	58.8	67.1
0844525350546	149.2	47.2	73.5	86.9	99.8	80.3	99.0	116.8	80.1	98.8	116.7
0844889349896	101.1	65.8	72.7	76.5	80.5	75.3	81.3	87.5	75.2	81.2	87.4
0844895352737	79.3	62.5	61.5	61.2	61.1	62.4	63.3	65.1	62.4	63.3	65.1
0845569351056	361.6	343.4	339.1	337.5	337.4	339.7	339.4	341.8	339.8	339.4	341.8
0845716351232	101.2	27.8	41.0	46.3	51.0	52.1	61.3	69.7	51.1	60.2	68.5
0845774349971	176.6	108.9	123.0	131.9	141.0	126.6	139.5	152.6	126.7	139.6	152.6
0845832350276	138.5	71.3	96.9	104.6	109.6	102.1	113.5	122.2	101.9	113.3	122.0
0845920348656	72.6	44.0	53.6	57.9	61.4	56.3	62.5	67.5	56.3	62.4	67.5
0846002348667	76.3	52.1	58.2	61.7	65.2	60.2	65.3	70.3	60.1	65.3	70.2
0846071350417	573.9	514.7	523.6	533.9	544.9	525.6	539.7	555.0	525.7	539.8	555.1
0846340349016	98.6	58.0	73.3	79.8	84.4	76.3	85.3	92.0	76.2	85.2	91.9
0846480349362	181.7	59.2	114.1	128.5	138.4	121.6	142.0	157.5	121.5	141.9	157.4
0846837350065	451.1	276.8	336.7	363.9	386.5	342.4	377.4	409.6	342.4	377.4	409.6
22002	52.0	21.5	32.0	36.4	40.1	33.8	40.2	45.7	33.8	40.3	45.7
23051.5	136.4	66.0	78.7	85.1	92.6	82.6	93.7	105.7	82.7	93.7	105.8
23065	87.6	38.0	53.3	59.5	64.7	57.8	66.9	74.7	57.7	66.7	74.4
23066	76.4	49.8	51.1	52.6	54.9	52.6	56.0	60.9	52.7	56.0	61.0
23073	158.9	141.5	139.3	137.4	134.6	143.6	142.8	141.5	143.2	142.3	140.9
23079	274.1	254.7	252.0	250.1	247.7	254.2	253.7	253.4	254.0	253.3	252.8
23088.5	64.3	0.9	15.7	23.3	31.2	19.5	31.0	43.1	19.6	31.1	43.1

Site ID	Hindcast	Current	Base Case			Regional Haze			Regional Haze + Red N		
	1860	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
5502	134.6	87.9	93.6	97.0	100.7	97.1	103.5	110.7	97.0	103.4	110.6
5532	90.0	3.0	31.1	39.4	46.2	36.4	49.4	60.8	36.4	49.3	60.8
5541	161.3	87.3	103.1	110.7	118.0	108.5	120.7	132.4	108.4	120.6	132.3
5550	77.8	-8.3	12.5	20.3	27.3	17.9	30.9	43.3	17.9	30.9	43.3
5568	284.1	238.0	238.2	238.3	239.7	239.9	242.9	248.9	239.9	242.9	248.9
6512	45.1	2.2	-1.3	-4.2	-8.9	1.5	2.6	4.7	1.5	2.5	4.7
6515	47.7	13.5	12.5	11.8	10.8	14.9	16.9	19.9	14.9	16.9	19.9
6519	73.5	56.0	53.7	51.8	48.6	54.9	54.3	53.8	54.8	54.3	53.8
6531	117.7	90.1	84.3	79.7	72.9	86.1	84.6	83.9	86.1	84.5	83.9
6573	46.3	-22.1	-27.1	-30.9	-36.7	-22.3	-18.8	-13.3	-22.3	-18.9	-13.3
6577	77.5	25.2	32.9	37.1	41.5	36.5	44.3	52.5	36.5	44.2	52.5
7000	159.6	67.1	98.7	107.2	114.2	104.8	119.1	131.5	104.8	119.0	131.5
7002	101.6	66.7	67.2	67.8	68.9	69.4	72.5	77.3	69.3	72.4	77.2
8006	32.7	-15.5	-18.5	-20.6	-23.3	-15.4	-13.1	-9.1	-15.5	-13.2	-9.2
8024	49.6	-30.2	-41.1	-51.0	-66.9	-35.0	-34.3	-31.4	-35.0	-34.4	-31.4
8068	64.9	-8.5	-15.3	-20.8	-29.2	-7.0	-4.8	-1.0	-7.3	-5.1	-1.3
8082	97.1	64.3	64.2	63.9	63.2	67.1	69.4	72.4	67.0	69.3	72.3
8084	108.8	17.7	13.4	14.3	19.7	20.2	30.4	46.1	20.2	30.3	46.0
8094	50.3	19.1	16.6	14.5	11.1	18.6	19.2	20.3	18.6	19.1	20.2
8129	29.2	-16.0	-18.4	-20.3	-23.3	-15.5	-13.4	-10.1	-15.6	-13.5	-10.1
9011	66.8	22.4	23.5	24.1	25.3	26.5	30.6	36.5	26.4	30.5	36.4
9031	85.1	50.5	53.8	55.9	58.4	55.8	60.1	65.7	55.7	60.1	65.6
9041	82.9	52.0	50.6	49.8	49.1	54.4	55.9	58.4	54.1	55.6	58.0
9042	68.5	15.3	14.4	15.2	17.3	18.0	22.9	30.7	17.9	22.9	30.6
9050	126.9	49.6	48.9	48.6	49.8	59.6	65.2	73.2	58.8	64.3	72.2
9055	99.9	43.8	44.2	44.4	44.4	52.3	56.1	61.0	51.6	55.4	60.2
9063	72.6	24.2	24.5	25.1	26.4	27.7	32.4	38.9	27.6	32.4	38.8
9073	107.0	46.7	45.5	45.6	46.7	50.8	56.2	63.6	50.6	55.9	63.3
9100	149.6	99.4	107.8	111.7	116.1	112.2	119.4	127.0	112.0	119.1	126.7

Site ID	Hindcast	Current	Base Case			Regional Haze			Regional Haze + Red N		
	1860	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
9104	64.0	-22.8	-12.3	-5.1	3.6	-6.2	7.2	22.3	-6.3	7.1	22.2
9105	79.3	22.2	27.4	30.4	33.7	31.1	38.4	46.6	31.0	38.4	46.5
9107	105.8	-8.6	17.6	29.4	41.8	24.5	43.1	61.9	24.5	43.1	61.9
9116	60.6	-8.3	23.0	30.9	35.9	28.1	40.1	48.3	28.1	40.0	48.2
9123	105.4	74.7	77.2	78.7	80.6	79.1	82.7	87.1	79.1	82.7	87.1
9144	116.1	67.0	72.4	76.5	82.2	75.3	82.6	92.0	75.2	82.6	91.9
9150	65.0	-6.9	8.9	16.3	23.1	13.6	25.8	37.1	13.6	25.7	37.1
9151	53.0	-25.3	-10.6	-2.8	4.8	-5.3	8.0	21.0	-5.3	8.0	20.9
9152	90.4	48.0	49.9	51.5	53.2	53.3	58.1	63.3	53.2	58.0	63.2
9153	43.8	-49.8	-21.9	-10.6	-0.4	-16.1	0.7	15.8	-16.1	0.7	15.7
9170	87.6	35.2	36.9	37.8	38.7	40.3	45.6	51.9	40.3	45.6	51.8
9171	188.2	110.3	111.7	117.5	127.3	116.6	128.1	143.6	116.6	128.1	143.5
9172	100.5	34.5	61.9	70.7	77.3	66.4	79.1	89.1	66.4	79.1	89.0
9174	74.9	20.9	36.7	42.4	47.0	40.1	48.9	56.5	40.1	48.8	56.5
DS04	52.6	-65.0	-38.8	-25.3	-11.8	-30.6	-10.0	10.2	-30.6	-10.0	10.2
DS09	49.8	-58.7	-44.1	-34.4	-22.8	-36.8	-18.9	0.4	-36.7	-18.9	0.5
DS19	65.5	-35.8	-28.0	-20.2	-9.8	-20.9	-5.1	13.6	-20.9	-5.1	13.6
DS50	49.0	-27.9	-29.3	-28.7	-25.8	-23.9	-16.0	-4.3	-23.9	-15.9	-4.2
OC02	73.0	-55.9	-16.6	0.2	14.3	-5.8	18.0	38.1	-6.0	17.8	37.8
OC08	46.5	-75.1	-34.8	-18.3	-4.1	-27.6	-4.3	15.7	-27.5	-4.2	15.8
OC35	83.7	-58.8	-7.8	12.3	28.6	0.5	28.0	50.4	0.6	28.1	50.5
OC79	103.0	10.2	17.0	23.4	31.3	26.1	39.4	54.6	25.8	39.1	54.2
VA524S	102.0	-13.6	-0.3	8.5	18.7	8.1	25.5	44.4	8.0	25.4	44.4
VA526S	198.8	100.6	92.9	92.5	99.2	99.9	109.4	127.2	99.9	109.3	127.2
VA531S	112.6	65.5	61.0	57.3	51.3	65.1	65.7	67.0	64.9	65.5	66.8
VA548S	125.5	20.6	43.3	54.7	66.1	50.0	67.6	85.2	49.8	67.5	85.0
VA555S	61.3	17.9	13.3	10.6	6.8	15.5	16.8	19.9	15.5	16.8	19.9
VA821S	171.5	78.6	51.2	51.7	62.9	60.0	72.9	95.2	60.0	72.9	95.2
WV523S	50.7	-39.7	-30.7	-23.8	-14.8	-24.1	-10.5	5.4	-24.3	-10.6	5.3

Site ID	Hindcast	Current	Base Case			Regional Haze			Regional Haze + Red N		
	1860	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
WV531S	59.9	-47.7	-15.0	-2.6	8.2	-7.9	10.6	26.8	-8.0	10.5	26.7
WV547S	217.2	70.3	121.4	140.7	156.5	131.8	158.1	180.5	131.5	157.8	180.1
WV548S	92.2	-26.1	-8.8	0.9	12.3	2.4	19.8	38.3	2.0	19.3	37.9
WV769S	154.2	33.1	64.4	76.4	87.7	73.8	92.5	110.3	73.6	92.2	110.0
WV770S	223.0	113.0	149.0	161.1	171.6	156.4	174.6	191.0	156.3	174.4	190.8
WV771S	226.6	126.5	133.2	137.7	144.7	140.9	152.6	167.4	140.7	152.4	167.1
WV785S	100.7	-60.0	-42.2	-34.2	-24.4	-29.9	-7.5	15.9	-29.9	-7.5	15.9
WV788S	93.1	-3.0	6.3	12.4	20.4	14.6	27.7	43.0	14.4	27.4	42.7
WV796S	110.8	42.0	38.3	34.9	32.0	43.1	46.8	53.3	43.1	46.8	53.3

Table A3-2. MAGIC modeled ANC ($\mu\text{eq/L}$) for year 2016 and deviations between year 2016 ANC and future ANC for years 2060, 2100, and 2170 under the three scenarios. Positive values for future years indicates and increase in ANC relative to year 2016 and negative values indicate a decrease in ANC relative to 2016.

Site ID	Current	Base Case			Regional Haze			Regional Haze + Red N		
	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
0819003359391	-14.1	9.3	15.1	21.4	12.0	21.1	30.7	12.0	21.0	30.7
0819333365729	21.4	-0.9	-1.6	-2.7	1.3	1.6	2.4	1.2	1.6	2.4
0819405365852	25.3	4.2	6.8	9.9	8.5	14.2	21.1	8.4	14.0	21.0
0819976365378	341.0	-2.0	-3.4	-4.9	-0.6	-0.2	1.3	-0.6	-0.2	1.3
0820288361949	132.8	4.1	6.6	9.0	6.2	11.4	17.3	6.2	11.4	17.3
0820575365023	288.7	-3.6	-6.0	-9.0	-2.4	-3.2	-3.4	-2.4	-3.3	-3.5
0820659362857	120.1	1.8	2.5	3.3	3.1	5.5	8.9	3.1	5.5	8.9
0821098362008	108.4	3.6	5.3	6.4	6.1	9.4	11.9	6.0	9.3	11.7
0821111362567	69.5	4.0	9.4	16.9	8.3	17.4	28.9	8.1	17.1	28.6
0821665364328	-1.8	15.9	24.0	32.8	21.1	33.9	47.2	21.0	33.8	47.1
0822058362619	26.6	26.8	36.1	43.7	31.4	44.8	56.2	31.3	44.7	56.1
0822102358016	27.3	0.9	2.0	3.8	3.4	6.6	11.2	3.3	6.5	11.0
0822122357913	26.6	2.0	3.8	6.4	4.4	8.3	13.6	4.3	8.2	13.4
0822144357431	35.6	-2.1	-3.5	-5.1	0.0	1.2	3.7	-0.1	1.1	3.6
0822446357370	24.3	1.7	3.6	6.5	4.7	9.1	15.0	4.6	8.9	14.8
0822486357318	17.5	0.8	1.6	3.2	3.7	7.0	11.9	3.6	6.8	11.7
0822632361472	30.9	18.9	26.3	32.5	22.0	32.7	41.9	22.0	32.7	41.9
0822811357260	33.0	-0.2	-0.3	-0.3	2.0	3.7	6.2	1.9	3.6	6.1
0823970361827	177.2	-4.6	-7.0	-8.6	-4.1	-5.6	-4.7	-4.2	-5.6	-4.8
0824227362028	62.0	27.9	40.5	50.8	31.4	47.9	61.9	31.4	47.9	61.9
0824312360996	14.9	18.4	27.2	35.2	21.8	34.0	45.1	21.8	34.0	45.1
0825384359725	146.1	-4.2	-6.7	-8.9	-1.3	-1.5	-0.4	-1.4	-1.7	-0.7
0825869361157	84.7	2.1	2.5	2.0	8.2	10.2	12.0	7.7	9.7	11.3
0826140361316	146.9	24.4	34.0	41.9	28.1	41.5	53.8	28.0	41.4	53.6
0826540361058	47.0	31.0	38.2	42.4	37.3	49.0	56.6	37.2	48.8	56.3

Site ID	Current	Base Case			Regional Haze			Regional Haze + Red N		
	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
0826728360724	31.6	3.3	5.5	8.0	4.1	7.5	11.3	4.2	7.6	11.4
0827495360190	88.4	5.4	5.9	5.9	16.6	20.0	21.4	15.7	18.9	20.2
0827728360271	97.2	27.0	38.8	48.4	30.5	46.2	59.6	30.5	46.2	59.7
0828146359682	61.0	38.9	47.3	53.1	47.4	63.0	75.8	47.4	63.0	75.8
0828261353375	40.4	-0.2	-0.1	0.4	0.5	1.7	3.9	0.6	1.8	4.0
0828670353323	18.1	-0.3	-0.1	0.5	0.9	3.1	6.6	0.9	3.1	6.6
0828817352953	21.5	19.2	24.4	27.8	24.9	33.2	38.9	24.7	32.9	38.6
0828920352772	39.5	2.9	5.1	7.9	4.7	8.6	13.5	4.7	8.5	13.4
0829067352780	24.6	21.8	26.4	29.3	26.0	34.0	39.0	26.0	34.0	39.0
0829079353270	28.7	1.2	2.6	4.9	2.2	5.1	9.3	2.2	5.1	9.3
0829160353045	44.0	1.8	4.1	7.6	3.0	7.3	13.2	3.0	7.3	13.1
0829184352865	21.9	24.1	30.7	34.3	28.4	38.2	44.0	28.3	38.1	43.9
0829194352886	14.6	17.7	22.1	24.6	22.2	29.2	33.5	22.1	29.1	33.3
0829321353099	39.0	2.1	4.2	7.2	3.1	6.6	11.3	3.1	6.6	11.3
0829630353646	44.9	-0.7	-1.1	-1.3	3.2	4.9	7.8	3.0	4.6	7.5
0829670359613	90.9	-0.6	-0.9	-1.4	0.0	0.5	1.3	0.0	0.5	1.3
0829674352788	48.0	0.0	0.4	1.2	1.1	2.6	5.1	1.1	2.6	5.1
0830494349738	77.9	-0.9	-1.5	-2.4	-0.4	-0.3	0.1	-0.4	-0.3	0.1
0830849349820	74.4	-1.0	-1.7	-2.6	-0.4	-0.4	0.0	-0.3	-0.3	0.1
0830946350205	48.5	-0.5	-0.8	-1.1	-0.2	0.2	1.0	-0.2	0.2	1.0
0831036359106	43.7	13.1	23.1	35.0	18.1	34.0	51.5	18.4	34.3	51.7
0831139350208	53.6	1.1	2.2	3.9	1.9	4.0	6.9	1.8	3.9	6.9
0831205358440	622.8	-2.2	-3.5	-4.9	-0.9	-0.3	1.3	-0.9	-0.4	1.3
0831285350075	73.5	-0.8	-1.2	-1.8	-0.4	-0.2	0.5	-0.4	-0.2	0.5
0831579358839	32.1	2.3	3.9	6.0	4.2	8.6	14.2	4.2	8.6	14.2
0831907358024	482.9	3.9	12.8	24.7	8.1	22.4	40.3	8.0	22.2	40.0
0832042358247	50.4	-2.0	-2.9	-3.6	-1.5	-1.2	0.1	-1.5	-1.1	0.2
0835047350176	29.1	-0.3	-0.4	-0.4	0.3	0.8	1.9	0.3	0.8	1.9
0835085350173	37.9	-0.3	-0.5	-0.7	0.2	0.8	1.7	0.2	0.7	1.7

Site ID	Current	Base Case			Regional Haze			Regional Haze + Red N		
	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
0839239352738	37.9	0.7	1.4	2.7	3.0	5.3	8.8	2.9	5.1	8.7
0839262352702	42.1	-0.3	-0.4	-0.4	0.6	1.6	3.3	0.6	1.6	3.2
0839336353542	101.1	-1.0	-1.7	-2.9	-0.6	-0.8	-0.9	-0.6	-0.8	-0.9
0839358353530	31.3	1.4	2.4	3.7	3.3	6.1	9.7	3.3	6.1	9.7
0839517353661	38.7	-0.2	-0.3	-0.3	0.5	1.5	3.3	0.5	1.5	3.3
0839594353679	44.0	4.6	8.0	11.9	6.2	11.3	17.0	6.2	11.3	17.0
0839829353633	23.3	12.2	16.4	19.3	15.4	21.6	25.9	15.3	21.5	25.8
0839976353481	7.5	7.1	10.5	13.5	11.6	16.7	21.3	11.4	16.5	21.0
0840110352961	20.5	8.7	13.2	17.2	13.1	19.6	25.4	12.8	19.3	25.1
0840139353542	26.1	11.0	15.7	19.7	16.7	23.9	29.9	16.4	23.5	29.6
0840233353666	32.3	20.7	29.2	36.1	33.5	46.6	57.4	32.6	45.7	56.4
0840303353155	-0.6	19.5	25.5	29.0	25.2	34.0	39.5	25.0	33.8	39.3
0840420353309	42.3	1.7	3.2	5.6	7.0	10.7	15.6	6.7	10.3	15.2
0840444353143	19.7	7.7	11.7	15.6	10.1	16.1	22.0	10.0	16.1	21.9
0840472353165	23.9	6.6	10.2	13.9	9.6	15.1	20.8	9.4	14.9	20.6
0840477353169	22.0	2.9	5.3	8.6	9.0	14.2	20.8	8.6	13.8	20.3
0840574353329	34.7	12.7	17.9	22.2	17.4	25.0	31.6	17.2	24.8	31.3
0840591352378	44.7	-0.2	0.2	1.3	1.8	3.8	7.3	1.7	3.7	7.2
0840609353308	40.3	16.0	21.8	25.8	22.2	30.9	37.1	21.9	30.5	36.8
0840675353310	51.8	3.1	5.8	9.6	9.3	14.6	21.3	8.9	14.2	20.8
0840745352655	45.5	3.4	6.1	9.3	6.4	10.9	16.4	6.3	10.8	16.2
0840802352619	41.2	11.8	16.2	19.4	14.5	20.9	25.8	14.4	20.8	25.7
0840876355009	20.7	26.4	32.5	36.5	30.7	40.8	47.9	30.7	40.8	47.9
0840886352889	38.0	3.8	6.3	9.5	7.6	12.1	17.6	7.4	11.8	17.3
0840893352584	21.8	3.5	5.8	8.6	7.8	12.5	18.3	7.6	12.2	18.0
0840999353179	119.7	1.3	2.5	4.5	2.7	5.4	9.0	2.7	5.3	9.0
0841126353049	71.2	4.4	7.5	11.0	7.1	12.5	18.7	7.1	12.5	18.7
0841405354390	60.3	26.1	34.7	39.9	29.1	41.1	49.1	29.1	41.1	49.1
0841965353483	123.4	-0.3	0.5	1.7	5.2	9.3	13.7	4.8	8.7	13.0

Site ID	Current	Base Case			Regional Haze			Regional Haze + Red N		
	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
0842048352868	48.1	25.9	31.7	36.1	31.6	42.1	50.6	31.6	42.0	50.5
0843145352310	165.9	-2.0	-0.3	3.6	-1.2	1.9	7.8	-1.2	1.9	7.8
0843377352707	176.7	-0.9	-1.5	-2.3	-0.7	-1.1	-1.5	-0.7	-1.1	-1.5
0843873352029	137.4	8.0	16.4	25.4	11.0	22.9	35.6	11.0	22.9	35.6
0844151352181	50.1	9.3	13.2	17.1	13.8	20.6	27.7	13.6	20.4	27.5
0844273352649	219.5	36.4	51.4	63.1	40.4	60.0	76.5	40.6	60.4	76.9
0844278351285	26.9	18.7	25.7	31.3	21.7	31.9	40.2	21.7	31.9	40.2
0844525350546	47.2	26.3	39.7	52.6	33.1	51.8	69.6	33.0	51.6	69.5
0844889349896	65.8	6.9	10.8	14.8	9.6	15.5	21.8	9.5	15.4	21.6
0844895352737	62.5	-1.0	-1.3	-1.4	-0.1	0.8	2.6	-0.1	0.8	2.6
0845569351056	343.4	-4.3	-5.9	-6.0	-3.7	-4.0	-1.6	-3.6	-3.9	-1.6
0845716351232	27.8	13.3	18.5	23.2	24.3	33.5	42.0	23.4	32.4	40.7
0845774349971	108.9	14.1	23.0	32.1	17.7	30.6	43.7	17.7	30.6	43.7
0845832350276	71.3	25.5	33.2	38.2	30.7	42.2	50.9	30.6	41.9	50.6
0845920348656	44.0	9.6	14.0	17.5	12.3	18.5	23.6	12.3	18.5	23.5
0846002348667	52.1	6.1	9.6	13.1	8.1	13.2	18.2	8.0	13.2	18.1
0846071350417	514.7	8.8	19.1	30.1	10.9	24.9	40.2	11.0	25.1	40.4
0846340349016	58.0	15.3	21.8	26.4	18.2	27.3	34.0	18.1	27.2	33.9
0846480349362	59.2	54.9	69.3	79.2	62.4	82.8	98.3	62.3	82.7	98.2
0846837350065	276.8	59.9	87.2	109.7	65.6	100.7	132.8	65.6	100.6	132.8
22002	21.5	10.5	15.0	18.6	12.3	18.7	24.2	12.3	18.8	24.2
23051.5	66.0	12.6	19.1	26.5	16.6	27.6	39.7	16.7	27.7	39.8
23065	38.0	15.3	21.6	26.7	19.9	29.0	36.7	19.7	28.8	36.5
23066	49.8	1.3	2.7	5.1	2.8	6.2	11.1	2.9	6.2	11.2
23073	141.5	-2.2	-4.1	-6.9	2.1	1.3	0.1	1.7	0.9	-0.6
23079	254.7	-2.7	-4.5	-7.0	-0.5	-0.9	-1.3	-0.7	-1.3	-1.9
23088.5	0.9	14.7	22.3	30.3	18.6	30.1	42.1	18.6	30.2	42.2
5502	87.9	5.7	9.0	12.7	9.1	15.6	22.8	9.0	15.5	22.7
5532	3.0	28.1	36.4	43.1	33.4	46.4	57.8	33.4	46.3	57.7

Site ID	Current	Base Case			Regional Haze			Regional Haze + Red N		
	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
5541	87.3	15.8	23.5	30.8	21.3	33.4	45.2	21.2	33.3	45.0
5550	-8.3	20.8	28.6	35.6	26.2	39.2	51.6	26.2	39.2	51.6
5568	238.0	0.2	0.4	1.7	1.9	4.9	10.9	1.9	4.9	10.9
6512	2.2	-3.5	-6.5	-11.1	-0.7	0.3	2.5	-0.8	0.3	2.5
6515	13.5	-1.0	-1.7	-2.7	1.4	3.4	6.4	1.4	3.4	6.4
6519	56.0	-2.2	-4.1	-7.3	-1.1	-1.6	-2.1	-1.1	-1.6	-2.1
6531	90.1	-5.8	-10.4	-17.2	-4.0	-5.6	-6.2	-4.0	-5.6	-6.2
6573	-22.1	-5.0	-8.8	-14.6	-0.2	3.2	8.8	-0.3	3.2	8.7
6577	25.2	7.6	11.8	16.3	11.3	19.0	27.3	11.2	19.0	27.2
7000	67.1	31.6	40.1	47.2	37.8	52.0	64.4	37.7	52.0	64.4
7002	66.7	0.5	1.1	2.2	2.7	5.9	10.6	2.6	5.8	10.5
8006	-15.5	-3.0	-5.0	-7.7	0.1	2.4	6.4	0.1	2.3	6.4
8024	-30.2	-10.9	-20.7	-36.7	-4.7	-4.1	-1.2	-4.8	-4.1	-1.2
8068	-8.5	-6.8	-12.4	-20.7	1.5	3.6	7.5	1.2	3.3	7.1
8082	64.3	-0.1	-0.4	-1.0	2.8	5.1	8.1	2.7	5.1	8.0
8084	17.7	-4.3	-3.4	2.0	2.5	12.7	28.4	2.5	12.6	28.3
8094	19.1	-2.4	-4.5	-8.0	-0.4	0.1	1.2	-0.5	0.1	1.2
8129	-16.0	-2.4	-4.3	-7.3	0.5	2.6	5.9	0.4	2.5	5.9
9011	22.4	1.1	1.8	2.9	4.2	8.3	14.1	4.1	8.2	14.0
9031	50.5	3.4	5.5	7.9	5.3	9.6	15.2	5.3	9.6	15.2
9041	52.0	-1.4	-2.2	-2.9	2.4	3.9	6.4	2.1	3.6	6.0
9042	15.3	-0.9	-0.1	2.0	2.7	7.7	15.4	2.6	7.6	15.3
9050	49.6	-0.6	-0.9	0.2	10.0	15.7	23.7	9.2	14.8	22.7
9055	43.8	0.4	0.6	0.6	8.5	12.3	17.2	7.8	11.6	16.4
9063	24.2	0.3	0.9	2.2	3.5	8.3	14.7	3.5	8.2	14.7
9073	46.7	-1.3	-1.1	-0.1	4.1	9.5	16.9	3.8	9.2	16.5
9100	99.4	8.4	12.3	16.6	12.8	19.9	27.6	12.6	19.7	27.3
9104	-22.8	10.5	17.7	26.4	16.6	30.0	45.1	16.5	29.9	45.0
9105	22.2	5.2	8.2	11.5	8.9	16.2	24.4	8.8	16.2	24.3

Site ID	Current	Base Case			Regional Haze			Regional Haze + Red N		
	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
9107	-8.6	26.3	38.1	50.4	33.1	51.8	70.6	33.1	51.7	70.5
9116	-8.3	31.2	39.2	44.2	36.4	48.3	56.6	36.3	48.3	56.5
9123	74.7	2.6	4.0	5.9	4.4	8.0	12.4	4.4	8.0	12.4
9144	67.0	5.4	9.5	15.2	8.3	15.7	25.0	8.3	15.6	25.0
9150	-6.9	15.8	23.2	30.0	20.5	32.7	44.0	20.5	32.6	44.0
9151	-25.3	14.7	22.5	30.1	20.0	33.3	46.3	20.0	33.2	46.2
9152	48.0	1.9	3.5	5.2	5.3	10.1	15.3	5.2	10.0	15.2
9153	-49.8	27.9	39.3	49.4	33.8	50.6	65.6	33.7	50.5	65.5
9170	35.2	1.6	2.5	3.5	5.1	10.4	16.6	5.0	10.4	16.6
9171	110.3	1.5	7.3	17.0	6.4	17.9	33.3	6.3	17.8	33.2
9172	34.5	27.3	36.2	42.8	31.9	44.6	54.6	31.8	44.5	54.5
9174	20.9	15.8	21.4	26.1	19.2	28.0	35.6	19.1	27.9	35.6
DS04	-65.0	26.2	39.7	53.2	34.4	55.0	75.2	34.4	55.0	75.2
DS09	-58.7	14.6	24.4	35.9	22.0	39.8	59.2	22.0	39.9	59.2
DS19	-35.8	7.7	15.6	25.9	14.9	30.7	49.4	14.9	30.7	49.4
DS50	-27.9	-1.4	-0.8	2.1	4.0	11.9	23.6	4.1	12.0	23.7
OC02	-55.9	39.3	56.1	70.2	50.1	73.9	93.9	49.9	73.6	93.7
OC08	-75.1	40.3	56.8	71.0	47.6	70.9	90.9	47.7	70.9	90.9
OC35	-58.8	51.0	71.1	87.3	59.3	86.8	109.2	59.4	86.8	109.2
OC79	10.2	6.8	13.2	21.1	15.9	29.2	44.4	15.6	28.9	44.0
VA524S	-13.6	13.3	22.1	32.3	21.7	39.1	58.0	21.7	39.0	58.0
VA526S	100.6	-7.8	-8.2	-1.4	-0.7	8.7	26.6	-0.8	8.7	26.6
VA531S	65.5	-4.4	-8.2	-14.2	-0.4	0.2	1.5	-0.6	0.0	1.3
VA548S	20.6	22.7	34.1	45.6	29.4	47.1	64.6	29.3	46.9	64.5
VA555S	17.9	-4.7	-7.4	-11.1	-2.4	-1.1	2.0	-2.4	-1.1	2.0
VA821S	78.6	-27.4	-26.9	-15.7	-18.6	-5.7	16.6	-18.6	-5.7	16.6
WV523S	-39.7	9.0	15.9	24.9	15.5	29.2	45.1	15.4	29.0	44.9
WV531S	-47.7	32.6	45.0	55.8	39.8	58.2	74.4	39.7	58.1	74.3
WV547S	70.3	51.1	70.4	86.2	61.5	87.9	110.2	61.2	87.5	109.8

Site ID	Current	Base Case			Regional Haze			Regional Haze + Red N		
	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
WV548S	-26.1	17.3	27.0	38.4	28.5	45.8	64.4	28.1	45.4	64.0
WV769S	33.1	31.4	43.3	54.6	40.8	59.4	77.3	40.5	59.1	76.9
WV770S	113.0	36.0	48.1	58.6	43.4	61.6	78.0	43.3	61.4	77.8
WV771S	126.5	6.7	11.2	18.2	14.4	26.1	40.9	14.2	25.9	40.6
WV785S	-60.0	17.8	25.8	35.6	30.1	52.5	75.8	30.1	52.5	75.8
WV788S	-3.0	9.3	15.5	23.5	17.6	30.7	46.0	17.4	30.5	45.8
WV796S	42.0	-3.7	-7.1	-10.0	1.1	4.8	11.3	1.1	4.8	11.2

Appendix 5. MAGIC Modeled Base Saturation Scenario Results

Table A4-1. Base saturation (%) scenario results from MAGIC modeling for years 1860, 2016, and years 2060, 2100, and 2170 under the three future scenarios.

Site ID	Hindcast	Current	Base Case			Regional Haze			Regional Haze + Red N		
	1860	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
0819003359391	3.0	2.4	2.4	2.4	2.4	2.4	2.4	2.5	2.4	2.4	2.5
0819333365729	10.3	10.1	10.0	10.0	9.9	10.0	10.0	10.0	10.0	10.0	10.0
0819405365852	10.9	9.3	8.7	8.4	8.2	8.7	8.5	8.5	8.7	8.5	8.5
0819976365378	39.6	34.7	32.4	31.2	30.0	32.5	31.6	31.2	32.5	31.6	31.1
0820288361949	27.1	23.0	21.2	20.2	19.3	21.2	20.5	20.2	21.2	20.5	20.2
0820575365023	42.2	37.8	35.4	33.9	32.1	35.5	34.4	33.3	35.5	34.3	33.3
0820659362857	12.7	11.1	10.4	10.0	9.7	10.5	10.2	10.0	10.5	10.2	10.0
0821098362008	70.7	66.9	65.3	64.4	63.2	65.4	64.7	64.3	65.4	64.7	64.3
0821111362567	11.7	9.4	9.1	9.2	9.4	9.2	9.4	9.8	9.2	9.4	9.8
0821665364328	11.9	9.4	8.7	8.7	8.8	8.8	8.9	9.2	8.8	8.9	9.2
0822058362619	37.9	30.2	29.8	30.3	31.3	29.9	30.7	32.4	29.9	30.7	32.4
0822102358016	9.7	9.0	8.8	8.7	8.7	8.8	8.8	8.8	8.8	8.8	8.8
0822122357913	10.9	9.9	9.8	9.8	9.8	9.8	9.8	10.0	9.8	9.8	10.0
0822144357431	11.0	10.3	10.0	9.8	9.5	10.0	9.9	9.7	10.0	9.9	9.7
0822446357370	11.0	10.0	9.9	9.9	10.0	9.9	10.0	10.2	9.9	10.0	10.2
0822486357318	12.2	11.0	10.7	10.6	10.6	10.7	10.7	10.9	10.7	10.7	10.9
0822632361472	24.6	21.6	21.2	21.2	21.5	21.2	21.4	22.0	21.2	21.4	22.0
0822811357260	61.0	60.2	59.8	59.5	59.1	59.8	59.6	59.3	59.8	59.6	59.3
0823970361827	14.7	11.9	10.5	9.9	9.3	10.6	10.1	9.8	10.6	10.1	9.8
0824227362028	16.1	9.0	9.8	10.7	11.7	9.9	11.1	12.8	9.9	11.1	12.8
0824312360996	14.6	11.4	11.3	11.7	12.4	11.4	12.0	12.9	11.4	12.0	12.9
0825384359725	11.9	9.6	8.9	8.5	8.2	9.0	8.9	8.9	9.0	8.8	8.8
0825869361157	46.1	41.2	39.7	38.7	37.4	40.0	39.4	38.9	39.9	39.4	38.8

Site ID	Hindcast	Current	Base Case			Regional Haze			Regional Haze + Red N		
	1860	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
0826140361316	36.0	9.6	11.9	14.5	17.6	12.5	16.4	21.9	12.5	16.4	21.9
0826540361058	28.2	21.3	21.8	22.3	23.0	21.9	22.9	24.1	21.9	22.8	24.1
0826728360724	18.2	17.5	17.4	17.3	17.4	17.4	17.4	17.5	17.4	17.4	17.5
0827495360190	6.8	5.3	5.5	5.6	5.6	5.7	5.9	6.0	5.7	5.9	5.9
0827728360271	24.0	12.7	13.4	14.6	16.1	13.6	15.3	17.9	13.6	15.3	17.9
0828146359682	44.1	22.2	21.3	21.6	22.1	21.6	22.6	24.8	21.6	22.6	24.8
0828261353375	8.6	8.3	8.1	8.0	8.0	8.1	8.1	8.1	8.1	8.1	8.1
0828670353323	7.2	6.8	6.6	6.5	6.5	6.6	6.6	6.5	6.6	6.6	6.5
0828817352953	17.5	14.2	13.9	14.1	14.3	14.0	14.3	15.0	14.0	14.3	14.9
0828920352772	17.2	16.1	15.8	15.7	15.8	15.8	15.8	16.0	15.8	15.8	16.0
0829067352780	34.7	26.8	27.9	29.0	30.2	28.0	29.6	31.6	28.0	29.6	31.6
0829079353270	6.9	6.4	6.3	6.3	6.3	6.3	6.3	6.4	6.3	6.3	6.4
0829160353045	7.1	6.4	6.2	6.2	6.3	6.2	6.3	6.4	6.2	6.3	6.4
0829184352865	12.4	10.5	10.8	11.1	11.4	10.9	11.3	11.8	10.9	11.3	11.8
0829194352886	22.8	19.1	19.4	19.9	20.5	19.5	20.3	21.3	19.5	20.3	21.3
0829321353099	11.1	9.8	9.6	9.6	9.8	9.6	9.7	10.0	9.6	9.7	10.0
0829630353646	21.2	19.7	19.2	18.9	18.5	19.2	19.0	18.9	19.2	19.0	18.9
0829670359613	51.5	50.9	50.6	50.3	49.8	50.6	50.3	49.9	50.6	50.3	49.9
0829674352788	17.1	16.4	16.2	16.1	16.0	16.2	16.1	16.1	16.2	16.1	16.1
0830494349738	13.7	13.3	13.2	13.0	12.9	13.2	13.1	12.9	13.2	13.1	12.9
0830849349820	17.0	16.6	16.4	16.3	16.1	16.4	16.3	16.2	16.4	16.3	16.2
0830946350205	8.3	8.1	8.1	8.0	8.0	8.1	8.0	8.0	8.1	8.0	8.0
0831036359106	10.5	7.0	6.3	6.3	6.6	6.4	6.5	7.2	6.4	6.5	7.2
0831139350208	9.5	9.1	9.1	9.1	9.1	9.1	9.1	9.2	9.1	9.1	9.2
0831205358440	21.9	19.8	18.9	18.4	18.0	18.9	18.6	18.5	18.9	18.6	18.5
0831285350075	9.4	9.1	9.0	9.0	8.9	9.0	9.0	9.0	9.0	9.0	9.0
0831579358839	19.5	18.2	17.4	17.0	16.6	17.5	17.1	16.9	17.5	17.1	16.9
0831907358024	24.6	15.9	15.4	16.1	17.3	15.7	17.0	19.1	15.7	17.0	19.0
0832042358247	14.7	13.8	13.5	13.3	13.1	13.5	13.3	13.3	13.5	13.3	13.3

Site ID	Hindcast	Current	Base Case			Regional Haze			Regional Haze + Red N		
	1860	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
0835047350176	7.7	7.6	7.5	7.5	7.4	7.5	7.5	7.4	7.5	7.5	7.4
0835085350173	8.4	8.3	8.2	8.2	8.1	8.2	8.2	8.1	8.2	8.2	8.1
0839239352738	9.4	8.8	8.6	8.6	8.5	8.6	8.6	8.7	8.6	8.6	8.7
0839262352702	10.6	10.3	10.1	10.1	10.0	10.1	10.1	10.0	10.1	10.1	10.0
0839336353542	40.9	39.9	39.2	38.7	37.9	39.2	38.8	38.1	39.2	38.8	38.1
0839358353530	28.2	27.6	27.3	27.0	26.7	27.3	27.1	26.9	27.3	27.1	26.9
0839517353661	13.4	13.1	12.9	12.8	12.6	12.9	12.8	12.7	12.9	12.8	12.7
0839594353679	6.2	5.7	5.7	5.7	5.8	5.7	5.7	5.9	5.7	5.7	5.9
0839829353633	8.7	7.3	7.4	7.6	7.8	7.4	7.7	8.1	7.4	7.7	8.1
0839976353481	9.1	8.2	8.1	8.1	8.2	8.2	8.2	8.4	8.2	8.2	8.4
0840110352961	7.4	5.9	6.1	6.3	6.5	6.2	6.5	6.8	6.2	6.5	6.8
0840139353542	6.7	5.0	5.0	5.2	5.4	5.1	5.4	5.8	5.1	5.4	5.8
0840233353666	20.1	12.4	12.8	13.4	14.1	13.2	14.4	15.6	13.2	14.3	15.5
0840303353155	5.8	4.5	4.7	4.9	5.1	4.8	5.1	5.3	4.8	5.1	5.3
0840420353309	10.9	9.5	9.3	9.3	9.3	9.4	9.4	9.6	9.4	9.4	9.6
0840444353143	7.3	6.5	6.3	6.3	6.3	6.3	6.3	6.5	6.3	6.3	6.5
0840472353165	7.7	6.9	6.7	6.7	6.7	6.7	6.8	6.9	6.7	6.7	6.9
0840477353169	10.7	9.2	9.1	9.0	9.1	9.1	9.2	9.4	9.1	9.2	9.4
0840574353329	13.0	10.8	10.7	10.9	11.2	10.8	11.1	11.7	10.8	11.1	11.7
0840591352378	8.7	8.0	7.8	7.7	7.7	7.8	7.8	7.8	7.8	7.8	7.8
0840609353308	8.9	7.3	7.3	7.4	7.5	7.4	7.6	7.9	7.4	7.6	7.9
0840675353310	21.1	17.5	17.1	17.1	17.3	17.3	17.5	18.1	17.2	17.5	18.1
0840745352655	15.8	14.1	13.8	13.8	14.0	13.9	14.0	14.3	13.9	14.0	14.3
0840802352619	28.3	26.6	26.4	26.5	26.7	26.5	26.7	27.1	26.5	26.7	27.1
0840876355009	49.4	41.4	41.2	41.6	42.4	41.3	42.1	43.7	41.3	42.1	43.7
0840886352889	16.2	14.4	14.0	13.9	13.9	14.0	14.1	14.4	14.0	14.1	14.3
0840893352584	18.3	16.8	16.3	16.1	15.8	16.3	16.2	16.2	16.3	16.2	16.1
0840999353179	48.0	43.3	42.2	42.0	42.2	42.4	42.4	43.2	42.4	42.4	43.1
0841126353049	21.5	19.1	18.3	18.2	18.2	18.4	18.4	18.7	18.4	18.4	18.7

Site ID	Hindcast	Current	Base Case			Regional Haze			Regional Haze + Red N		
	1860	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
0841405354390	10.2	8.3	8.7	9.0	9.3	8.8	9.2	9.6	8.8	9.2	9.6
0841965353483	40.0	28.3	26.2	25.2	24.0	26.8	26.7	27.1	26.8	26.5	26.9
0842048352868	26.9	18.5	18.3	18.7	19.4	18.4	19.2	20.6	18.4	19.2	20.6
0843145352310	17.0	12.8	11.9	12.0	12.8	12.0	12.4	13.6	12.0	12.4	13.6
0843377352707	48.6	46.8	45.8	45.1	44.1	45.8	45.2	44.6	45.8	45.2	44.6
0843873352029	21.3	8.5	7.8	8.5	9.6	8.0	9.1	11.4	8.0	9.1	11.4
0844151352181	47.1	44.2	43.2	42.8	42.4	43.3	43.1	43.1	43.3	43.0	43.0
0844273352649	9.6	4.3	5.4	6.4	7.3	5.5	6.8	8.2	5.5	6.8	8.2
0844278351285	40.8	39.1	38.5	38.3	38.0	38.5	38.4	38.4	38.5	38.4	38.4
0844525350546	19.3	11.3	11.1	11.6	12.4	11.3	12.1	13.4	11.3	12.1	13.4
0844889349896	26.3	24.1	23.6	23.4	23.4	23.6	23.6	23.8	23.6	23.6	23.8
0844895352737	5.7	5.4	5.4	5.3	5.3	5.4	5.4	5.4	5.4	5.4	5.4
0845569351056	21.0	18.3	17.1	16.6	16.3	17.2	16.8	17.0	17.2	16.8	17.0
0845716351232	41.3	29.4	28.2	28.1	28.4	28.7	29.4	30.7	28.7	29.3	30.5
0845774349971	20.5	11.3	10.9	11.4	12.3	11.0	11.8	13.4	11.0	11.8	13.4
0845832350276	35.5	24.7	24.4	24.6	25.0	24.6	25.5	26.9	24.6	25.5	26.9
0845920348656	10.0	9.1	9.1	9.2	9.4	9.2	9.3	9.6	9.2	9.3	9.6
0846002348667	8.8	8.2	8.2	8.3	8.4	8.2	8.4	8.5	8.2	8.4	8.5
0846071350417	13.5	9.9	10.0	10.6	11.3	10.1	10.9	12.0	10.1	10.9	12.0
0846340349016	7.5	6.2	6.5	6.7	6.9	6.5	6.8	7.1	6.5	6.8	7.1
0846480349362	41.0	13.9	18.3	21.2	24.0	18.9	23.2	28.7	18.8	23.2	28.7
0846837350065	43.2	9.6	15.9	20.7	25.7	16.5	22.8	30.6	16.5	22.8	30.6
22002	54.4	53.2	52.9	52.8	52.8	52.9	52.9	53.1	52.9	52.9	53.1
23051.5	31.0	21.5	19.1	18.6	18.7	19.2	19.1	20.1	19.3	19.1	20.1
23065	13.0	10.8	10.6	10.6	10.7	10.6	10.8	11.2	10.6	10.8	11.1
23066	3.5	3.3	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
23073	75.3	70.6	68.9	67.5	65.2	69.2	68.3	66.9	69.2	68.2	66.7
23079	80.0	73.1	71.2	69.8	67.9	71.6	70.9	70.3	71.5	70.8	70.0
23088.5	12.2	10.6	10.2	10.2	10.3	10.3	10.3	10.6	10.3	10.3	10.6

Site ID	Hindcast	Current	Base Case			Regional Haze			Regional Haze + Red N		
	1860	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
5502	54.5	49.8	48.0	47.2	46.7	48.1	47.6	47.7	48.1	47.6	47.7
5532	23.5	18.9	17.5	17.0	16.8	17.6	17.3	17.6	17.6	17.3	17.6
5541	84.9	83.7	83.2	82.8	82.4	83.2	82.9	82.7	83.2	82.9	82.7
5550	32.9	29.7	28.3	27.6	27.0	28.4	27.9	27.6	28.4	27.9	27.6
5568	38.6	24.1	21.0	20.2	20.0	21.3	21.1	22.5	21.3	21.1	22.5
6512	33.6	32.6	31.9	31.4	30.6	32.0	31.5	30.9	32.0	31.5	30.9
6515	38.7	37.8	37.2	36.8	36.3	37.3	36.9	36.5	37.3	36.9	36.5
6519	33.4	32.7	32.2	31.9	31.3	32.2	31.9	31.5	32.2	31.9	31.5
6531	20.8	18.0	16.1	14.7	12.8	16.2	14.9	13.6	16.2	14.9	13.6
6573	39.5	38.2	37.4	36.7	35.6	37.4	36.8	36.1	37.4	36.8	36.1
6577	23.7	21.8	21.0	20.5	20.0	21.0	20.6	20.4	21.0	20.6	20.4
7000	16.7	9.6	9.2	9.4	9.8	9.3	9.7	10.8	9.3	9.7	10.8
7002	12.8	11.6	11.1	10.8	10.5	11.1	10.9	10.8	11.1	10.9	10.8
8006	16.2	15.3	14.8	14.4	14.0	14.8	14.5	14.3	14.8	14.5	14.3
8024	13.9	13.1	12.6	12.2	11.6	12.6	12.3	11.9	12.6	12.3	11.9
8068	15.3	14.3	13.7	13.2	12.5	13.7	13.3	12.9	13.7	13.3	12.9
8082	83.7	82.5	81.7	81.0	80.0	81.7	81.2	80.4	81.7	81.2	80.4
8084	14.5	11.3	9.9	9.2	8.8	9.9	9.4	9.4	9.9	9.4	9.4
8094	32.5	32.0	31.7	31.4	31.0	31.7	31.5	31.2	31.7	31.5	31.2
8129	29.2	28.6	28.2	27.8	27.3	28.2	27.9	27.5	28.2	27.9	27.5
9011	17.1	16.1	15.6	15.3	14.9	15.6	15.4	15.2	15.6	15.4	15.2
9031	73.4	72.0	71.3	70.8	70.4	71.3	70.9	70.7	71.3	70.9	70.7
9041	33.7	30.9	29.7	28.9	27.9	29.8	29.2	28.6	29.8	29.2	28.6
9042	10.8	9.4	8.9	8.6	8.3	8.9	8.7	8.6	8.9	8.7	8.6
9050	22.5	17.9	16.4	15.6	14.8	16.5	16.0	15.8	16.5	16.0	15.8
9055	51.9	46.1	43.8	42.3	40.4	44.0	43.0	42.0	44.0	42.9	41.9
9063	29.7	27.4	26.2	25.4	24.4	26.2	25.6	25.0	26.2	25.6	25.0
9073	16.2	13.6	12.5	11.9	11.2	12.5	12.1	11.8	12.5	12.1	11.8
9100	14.8	12.0	11.5	11.4	11.4	11.6	11.6	11.9	11.6	11.6	11.9

Site ID	Hindcast	Current	Base Case			Regional Haze			Regional Haze + Red N		
	1860	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
9104	10.8	9.4	9.0	8.8	8.8	9.0	8.9	9.0	9.0	8.9	9.0
9105	30.6	28.9	27.9	27.3	26.4	28.0	27.4	26.9	28.0	27.4	26.9
9107	18.5	14.9	13.9	13.7	13.8	14.0	14.0	14.4	14.0	14.0	14.4
9116	35.6	32.7	32.2	32.0	31.9	32.2	32.2	32.4	32.2	32.2	32.4
9123	53.7	51.4	50.2	49.5	48.7	50.3	49.7	49.3	50.3	49.7	49.3
9144	12.3	10.6	10.1	10.0	10.1	10.2	10.2	10.4	10.1	10.2	10.4
9150	19.9	19.4	19.2	19.0	18.7	19.2	19.0	18.8	19.2	19.0	18.8
9151	9.5	9.4	9.3	9.2	9.1	9.3	9.2	9.2	9.3	9.2	9.2
9152	41.7	39.7	38.6	37.8	36.9	38.6	38.0	37.4	38.6	38.0	37.4
9153	17.0	15.3	14.7	14.6	14.6	14.8	14.7	14.9	14.8	14.7	14.9
9170	24.8	23.4	22.5	21.9	21.2	22.6	22.1	21.6	22.6	22.1	21.6
9171	17.8	11.7	10.2	9.9	10.1	10.3	10.2	10.9	10.3	10.2	10.9
9172	20.1	15.4	15.6	16.1	16.9	15.7	16.5	17.7	15.7	16.5	17.7
9174	41.3	38.6	37.5	37.0	36.6	37.6	37.2	37.1	37.6	37.2	37.1
DS04	7.3	5.9	5.6	5.6	5.7	5.6	5.7	6.0	5.6	5.7	6.0
DS09	7.1	5.9	5.6	5.5	5.5	5.6	5.6	5.8	5.6	5.6	5.8
DS19	7.3	5.9	5.5	5.5	5.5	5.6	5.6	5.8	5.6	5.6	5.8
DS50	6.8	6.0	5.7	5.6	5.5	5.7	5.6	5.7	5.7	5.6	5.7
OC02	7.3	5.4	5.6	5.7	5.9	5.6	5.9	6.2	5.6	5.9	6.2
OC08	6.7	5.4	5.4	5.5	5.7	5.4	5.6	5.9	5.4	5.6	5.9
OC35	7.2	5.4	5.4	5.6	5.8	5.5	5.8	6.2	5.5	5.8	6.2
OC79	7.1	5.5	5.3	5.3	5.4	5.4	5.5	5.7	5.4	5.5	5.7
VA524S	11.4	9.4	8.5	8.3	8.1	8.6	8.4	8.6	8.6	8.4	8.6
VA526S	8.4	6.4	5.4	5.1	5.0	5.5	5.2	5.4	5.5	5.2	5.4
VA531S	10.5	10.1	9.8	9.6	9.3	9.9	9.7	9.4	9.9	9.7	9.4
VA548S	10.7	8.8	8.3	8.1	8.2	8.3	8.3	8.5	8.3	8.3	8.5
VA555S	11.3	10.7	10.4	10.3	10.1	10.5	10.3	10.2	10.5	10.3	10.2
VA821S	10.1	5.5	3.6	3.3	3.3	3.7	3.6	3.9	3.7	3.6	3.9
WV523S	7.2	5.9	5.7	5.6	5.7	5.7	5.7	5.9	5.7	5.7	5.9

Site ID	Hindcast	Current	Base Case			Regional Haze			Regional Haze + Red N		
	1860	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
WV531S	12.8	11.1	10.6	10.5	10.4	10.6	10.6	10.8	10.6	10.6	10.8
WV547S	11.9	6.2	6.7	7.2	7.9	6.8	7.6	8.8	6.8	7.6	8.8
WV548S	10.5	8.3	7.7	7.7	7.7	7.8	7.9	8.1	7.8	7.9	8.1
WV769S	14.2	10.5	9.8	9.7	9.8	9.9	9.9	10.4	9.9	9.9	10.4
WV770S	23.6	11.6	11.8	12.7	13.9	12.0	13.3	15.5	12.0	13.3	15.5
WV771S	15.1	10.0	8.6	8.3	8.4	8.7	8.7	9.2	8.7	8.7	9.2
WV785S	9.7	8.3	7.6	7.2	6.8	7.6	7.3	7.2	7.6	7.3	7.2
WV788S	11.4	9.5	8.9	8.6	8.5	8.9	8.8	8.9	8.9	8.8	8.9
WV796S	13.2	12.1	11.3	10.8	10.2	11.3	10.9	10.6	11.3	10.9	10.6

Table A4-2. MAGIC modeled base saturation (%) for year 2016 and deviations between year 2016 base saturation and future base saturation for years 2060, 2100, and 2170 under the three scenarios. Positive values for future years indicates an increase in base saturation relative to year 2016 and negative values indicate a decrease in base saturation relative to 2016.

Site ID	Current	Base Case			Regional Haze			Regional Haze + Red N		
	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
0819003359391	2.4	-0.1	-0.1	0.0	-0.1	0.0	0.1	-0.1	0.0	0.1
0819333365729	10.1	-0.1	-0.1	-0.2	-0.1	-0.1	-0.2	-0.1	-0.1	-0.2
0819405365852	9.3	-0.6	-0.9	-1.1	-0.6	-0.8	-0.8	-0.6	-0.8	-0.8
0819976365378	34.7	-2.3	-3.5	-4.7	-2.2	-3.1	-3.5	-2.2	-3.1	-3.6
0820288361949	23.0	-1.9	-2.9	-3.7	-1.8	-2.6	-2.8	-1.8	-2.6	-2.8
0820575365023	37.8	-2.4	-3.9	-5.7	-2.2	-3.4	-4.4	-2.2	-3.4	-4.5
0820659362857	11.1	-0.7	-1.1	-1.5	-0.7	-1.0	-1.2	-0.7	-1.0	-1.2
0821098362008	66.9	-1.6	-2.5	-3.6	-1.5	-2.2	-2.6	-1.5	-2.2	-2.6
0821111362567	9.4	-0.3	-0.2	0.0	-0.3	0.0	0.4	-0.3	-0.1	0.4
0821665364328	9.4	-0.6	-0.7	-0.5	-0.6	-0.5	-0.1	-0.6	-0.5	-0.1
0822058362619	30.2	-0.4	0.0	1.0	-0.3	0.5	2.2	-0.3	0.5	2.2
0822102358016	9.0	-0.2	-0.3	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
0822122357913	9.9	-0.2	-0.2	-0.2	-0.1	-0.1	0.1	-0.1	-0.1	0.1
0822144357431	10.3	-0.3	-0.5	-0.8	-0.3	-0.5	-0.7	-0.3	-0.5	-0.7
0822446357370	10.0	-0.1	-0.1	0.0	-0.1	0.0	0.2	-0.1	0.0	0.2
0822486357318	11.0	-0.3	-0.4	-0.4	-0.3	-0.3	-0.1	-0.3	-0.3	-0.2
0822632361472	21.6	-0.4	-0.4	-0.2	-0.4	-0.2	0.3	-0.4	-0.2	0.3
0822811357260	60.2	-0.4	-0.7	-1.1	-0.4	-0.6	-0.9	-0.4	-0.6	-0.9
0823970361827	11.9	-1.3	-2.0	-2.6	-1.3	-1.8	-2.0	-1.3	-1.8	-2.0
0824227362028	9.0	0.7	1.7	2.7	0.9	2.1	3.7	0.9	2.1	3.7
0824312360996	11.4	-0.1	0.3	0.9	0.0	0.6	1.4	0.0	0.6	1.4
0825384359725	9.6	-0.6	-1.0	-1.4	-0.5	-0.7	-0.7	-0.5	-0.7	-0.7
0825869361157	41.2	-1.4	-2.4	-3.7	-1.2	-1.7	-2.2	-1.2	-1.8	-2.3
0826140361316	9.6	2.3	4.9	8.0	2.9	6.8	12.3	2.8	6.8	12.2
0826540361058	21.3	0.4	1.0	1.6	0.6	1.5	2.8	0.6	1.5	2.8

Site ID	Current	Base Case			Regional Haze			Regional Haze + Red N		
	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
0826728360724	17.5	-0.2	-0.2	-0.2	-0.2	-0.2	0.0	-0.2	-0.2	0.0
0827495360190	5.3	0.2	0.3	0.3	0.4	0.6	0.6	0.4	0.5	0.6
0827728360271	12.7	0.8	1.9	3.4	0.9	2.6	5.2	0.9	2.6	5.2
0828146359682	22.2	-0.9	-0.6	-0.1	-0.6	0.4	2.6	-0.6	0.4	2.6
0828261353375	8.3	-0.1	-0.2	-0.3	-0.1	-0.2	-0.2	-0.1	-0.2	-0.2
0828670353323	6.8	-0.2	-0.3	-0.4	-0.2	-0.2	-0.3	-0.2	-0.2	-0.3
0828817352953	14.2	-0.2	-0.1	0.2	-0.1	0.2	0.8	-0.1	0.2	0.8
0828920352772	16.1	-0.3	-0.4	-0.3	-0.3	-0.3	-0.1	-0.3	-0.3	-0.1
0829067352780	26.8	1.0	2.1	3.4	1.2	2.7	4.8	1.2	2.7	4.7
0829079353270	6.4	-0.1	-0.2	-0.1	-0.1	-0.1	0.0	-0.1	-0.1	0.0
0829160353045	6.4	-0.1	-0.1	-0.1	-0.1	-0.1	0.1	-0.1	-0.1	0.1
0829184352865	10.5	0.4	0.7	1.0	0.4	0.9	1.3	0.4	0.9	1.3
0829194352886	19.1	0.3	0.8	1.5	0.5	1.2	2.3	0.4	1.2	2.3
0829321353099	9.8	-0.3	-0.2	-0.1	-0.2	-0.1	0.2	-0.2	-0.1	0.2
0829630353646	19.7	-0.5	-0.9	-1.2	-0.5	-0.7	-0.8	-0.5	-0.7	-0.8
0829670359613	50.9	-0.4	-0.7	-1.2	-0.4	-0.6	-1.0	-0.4	-0.6	-1.0
0829674352788	16.4	-0.2	-0.3	-0.4	-0.2	-0.3	-0.3	-0.2	-0.3	-0.3
0830494349738	13.3	-0.2	-0.3	-0.5	-0.2	-0.3	-0.4	-0.2	-0.3	-0.4
0830849349820	16.6	-0.2	-0.3	-0.5	-0.2	-0.3	-0.4	-0.2	-0.3	-0.4
0830946350205	8.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
0831036359106	7.0	-0.7	-0.7	-0.4	-0.6	-0.5	0.2	-0.6	-0.5	0.2
0831139350208	9.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1
0831205358440	19.8	-0.9	-1.4	-1.8	-0.9	-1.2	-1.4	-0.9	-1.2	-1.4
0831285350075	9.1	-0.1	-0.2	-0.3	-0.1	-0.2	-0.2	-0.1	-0.2	-0.2
0831579358839	18.2	-0.7	-1.1	-1.5	-0.7	-1.0	-1.2	-0.7	-1.0	-1.2
0831907358024	15.9	-0.5	0.2	1.4	-0.2	1.1	3.1	-0.2	1.0	3.1
0832042358247	13.8	-0.4	-0.6	-0.7	-0.4	-0.5	-0.5	-0.4	-0.5	-0.5
0835047350176	7.6	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
0835085350173	8.3	-0.1	-0.1	-0.2	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1

Site ID	Current	Base Case			Regional Haze			Regional Haze + Red N		
	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
0839239352738	8.8	-0.1	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
0839262352702	10.3	-0.1	-0.2	-0.3	-0.1	-0.2	-0.3	-0.1	-0.2	-0.3
0839336353542	39.9	-0.6	-1.2	-2.0	-0.6	-1.1	-1.7	-0.6	-1.1	-1.7
0839358353530	27.6	-0.3	-0.6	-0.9	-0.3	-0.5	-0.7	-0.3	-0.5	-0.7
0839517353661	13.1	-0.2	-0.3	-0.4	-0.2	-0.3	-0.4	-0.2	-0.3	-0.4
0839594353679	5.7	0.0	0.0	0.1	0.0	0.1	0.2	0.0	0.1	0.2
0839829353633	7.3	0.1	0.3	0.5	0.1	0.4	0.8	0.1	0.4	0.8
0839976353481	8.2	-0.1	-0.1	0.0	0.0	0.0	0.2	0.0	0.0	0.2
0840110352961	5.9	0.1	0.3	0.5	0.2	0.5	0.9	0.2	0.5	0.8
0840139353542	5.0	0.0	0.1	0.3	0.1	0.3	0.8	0.1	0.3	0.7
0840233353666	12.4	0.4	1.0	1.7	0.8	2.0	3.3	0.8	1.9	3.2
0840303353155	4.5	0.2	0.4	0.6	0.3	0.6	0.8	0.3	0.6	0.8
0840420353309	9.5	-0.2	-0.3	-0.3	-0.1	-0.1	0.1	-0.1	-0.1	0.1
0840444353143	6.5	-0.2	-0.2	-0.1	-0.2	-0.1	0.0	-0.2	-0.1	0.0
0840472353165	6.9	-0.2	-0.2	-0.1	-0.1	-0.1	0.0	-0.1	-0.1	0.0
0840477353169	9.2	-0.1	-0.2	-0.1	-0.1	0.0	0.2	-0.1	0.0	0.2
0840574353329	10.8	-0.1	0.1	0.4	0.0	0.4	0.9	0.0	0.3	0.9
0840591352378	8.0	-0.2	-0.3	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
0840609353308	7.3	0.0	0.1	0.3	0.1	0.3	0.7	0.1	0.3	0.6
0840675353310	17.5	-0.4	-0.4	-0.2	-0.2	0.1	0.7	-0.2	0.0	0.6
0840745352655	14.1	-0.3	-0.2	-0.1	-0.2	-0.1	0.3	-0.2	-0.1	0.3
0840802352619	26.6	-0.1	-0.1	0.1	-0.1	0.1	0.5	-0.1	0.1	0.5
0840876355009	41.4	-0.2	0.2	1.0	-0.1	0.7	2.2	-0.1	0.7	2.2
0840886352889	14.4	-0.4	-0.5	-0.4	-0.3	-0.3	0.0	-0.3	-0.3	0.0
0840893352584	16.8	-0.5	-0.8	-1.0	-0.5	-0.6	-0.7	-0.5	-0.6	-0.7
0840999353179	43.3	-1.0	-1.3	-1.1	-0.9	-0.8	-0.1	-0.9	-0.9	-0.1
0841126353049	19.1	-0.7	-0.9	-0.9	-0.7	-0.7	-0.4	-0.7	-0.7	-0.4
0841405354390	8.3	0.5	0.8	1.0	0.5	0.9	1.4	0.5	0.9	1.4
0841965353483	28.3	-2.0	-3.1	-4.2	-1.5	-1.6	-1.2	-1.5	-1.7	-1.4

Site ID	Current	Base Case			Regional Haze			Regional Haze + Red N		
	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
0842048352868	18.5	-0.2	0.2	0.9	-0.1	0.7	2.1	-0.1	0.7	2.1
0843145352310	12.8	-0.9	-0.8	-0.1	-0.9	-0.5	0.8	-0.9	-0.5	0.8
0843377352707	46.8	-1.0	-1.8	-2.7	-1.0	-1.6	-2.3	-1.0	-1.6	-2.2
0843873352029	8.5	-0.7	0.0	1.2	-0.5	0.6	2.9	-0.5	0.6	2.9
0844151352181	44.2	-1.0	-1.4	-1.8	-0.9	-1.1	-1.1	-0.9	-1.2	-1.2
0844273352649	4.3	1.1	2.1	3.0	1.2	2.5	3.9	1.2	2.5	3.9
0844278351285	39.1	-0.6	-0.8	-1.1	-0.6	-0.7	-0.7	-0.6	-0.7	-0.7
0844525350546	11.3	-0.2	0.3	1.1	0.0	0.8	2.1	0.0	0.8	2.1
0844889349896	24.1	-0.5	-0.7	-0.7	-0.5	-0.5	-0.3	-0.5	-0.5	-0.3
0844895352737	5.4	-0.1	-0.1	-0.1	0.0	-0.1	0.0	0.0	-0.1	0.0
0845569351056	18.3	-1.2	-1.7	-2.0	-1.1	-1.5	-1.3	-1.1	-1.5	-1.3
0845716351232	29.4	-1.2	-1.3	-1.0	-0.7	0.0	1.3	-0.8	-0.1	1.1
0845774349971	11.3	-0.5	0.0	0.9	-0.3	0.4	2.1	-0.3	0.4	2.1
0845832350276	24.7	-0.3	-0.1	0.3	-0.1	0.8	2.2	-0.1	0.8	2.2
0845920348656	9.1	0.0	0.2	0.3	0.1	0.3	0.5	0.1	0.3	0.5
0846002348667	8.2	0.0	0.1	0.2	0.1	0.2	0.3	0.1	0.2	0.3
0846071350417	9.9	0.2	0.7	1.4	0.3	1.0	2.1	0.3	1.0	2.1
0846340349016	6.2	0.3	0.5	0.6	0.3	0.6	0.9	0.3	0.6	0.9
0846480349362	13.9	4.4	7.3	10.1	4.9	9.3	14.8	4.9	9.3	14.8
0846837350065	9.6	6.3	11.1	16.1	6.9	13.2	21.0	6.9	13.2	21.0
22002	53.2	-0.4	-0.4	-0.4	-0.3	-0.4	-0.2	-0.3	-0.4	-0.2
23051.5	21.5	-2.4	-2.9	-2.8	-2.3	-2.4	-1.4	-2.2	-2.4	-1.4
23065	10.8	-0.3	-0.3	-0.1	-0.2	-0.1	0.3	-0.2	-0.1	0.3
23066	3.3	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	-0.1	-0.1	0.0
23073	70.6	-1.6	-3.0	-5.4	-1.3	-2.2	-3.7	-1.4	-2.3	-3.8
23079	73.1	-1.9	-3.3	-5.2	-1.5	-2.1	-2.8	-1.5	-2.3	-3.0
23088.5	10.6	-0.4	-0.4	-0.3	-0.4	-0.3	0.0	-0.4	-0.3	0.0
5502	49.8	-1.8	-2.6	-3.1	-1.7	-2.2	-2.1	-1.7	-2.2	-2.1
5532	18.9	-1.4	-1.9	-2.1	-1.3	-1.6	-1.3	-1.3	-1.6	-1.3

Site ID	Current	Base Case			Regional Haze			Regional Haze + Red N		
	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
5541	83.7	-0.5	-0.9	-1.3	-0.5	-0.8	-1.0	-0.5	-0.8	-1.0
5550	29.7	-1.4	-2.1	-2.8	-1.3	-1.9	-2.1	-1.3	-1.9	-2.1
5568	24.1	-3.1	-4.0	-4.1	-2.9	-3.1	-1.6	-2.9	-3.1	-1.6
6512	32.6	-0.7	-1.2	-2.0	-0.6	-1.1	-1.7	-0.6	-1.1	-1.7
6515	37.8	-0.5	-0.9	-1.5	-0.5	-0.9	-1.3	-0.5	-0.9	-1.3
6519	32.7	-0.5	-0.8	-1.4	-0.4	-0.8	-1.2	-0.4	-0.8	-1.2
6531	18.0	-1.9	-3.4	-5.3	-1.9	-3.1	-4.4	-1.9	-3.1	-4.4
6573	38.2	-0.9	-1.6	-2.6	-0.9	-1.5	-2.2	-0.9	-1.5	-2.2
6577	21.8	-0.8	-1.3	-1.8	-0.8	-1.2	-1.4	-0.8	-1.2	-1.4
7000	9.6	-0.4	-0.2	0.2	-0.3	0.1	1.2	-0.3	0.1	1.2
7002	11.6	-0.5	-0.8	-1.1	-0.5	-0.7	-0.9	-0.5	-0.7	-0.9
8006	15.3	-0.5	-0.8	-1.2	-0.5	-0.7	-0.9	-0.5	-0.7	-1.0
8024	13.1	-0.5	-0.9	-1.5	-0.5	-0.9	-1.3	-0.5	-0.9	-1.3
8068	14.3	-0.6	-1.1	-1.8	-0.6	-0.9	-1.4	-0.6	-0.9	-1.4
8082	82.5	-0.8	-1.5	-2.4	-0.8	-1.3	-2.0	-0.8	-1.3	-2.0
8084	11.3	-1.5	-2.2	-2.6	-1.4	-1.9	-2.0	-1.4	-1.9	-2.0
8094	32.0	-0.3	-0.6	-1.0	-0.3	-0.6	-0.9	-0.3	-0.6	-0.9
8129	28.6	-0.4	-0.8	-1.4	-0.4	-0.7	-1.2	-0.4	-0.7	-1.2
9011	16.1	-0.5	-0.8	-1.2	-0.5	-0.7	-0.9	-0.5	-0.7	-0.9
9031	72.0	-0.7	-1.1	-1.6	-0.7	-1.0	-1.3	-0.7	-1.0	-1.3
9041	30.9	-1.2	-2.0	-3.0	-1.1	-1.7	-2.3	-1.1	-1.7	-2.3
9042	9.4	-0.6	-0.9	-1.1	-0.5	-0.8	-0.8	-0.5	-0.8	-0.8
9050	17.9	-1.5	-2.3	-3.1	-1.3	-1.8	-2.0	-1.3	-1.8	-2.1
9055	46.1	-2.3	-3.8	-5.6	-2.0	-3.1	-4.1	-2.1	-3.1	-4.2
9063	27.4	-1.2	-2.1	-3.0	-1.2	-1.9	-2.5	-1.2	-1.9	-2.5
9073	13.6	-1.1	-1.7	-2.4	-1.1	-1.5	-1.8	-1.1	-1.5	-1.8
9100	12.0	-0.5	-0.6	-0.7	-0.4	-0.4	-0.1	-0.4	-0.5	-0.2
9104	9.4	-0.4	-0.6	-0.6	-0.4	-0.5	-0.4	-0.4	-0.5	-0.4
9105	28.9	-1.0	-1.6	-2.5	-1.0	-1.5	-2.1	-1.0	-1.5	-2.1

Site ID	Current	Base Case			Regional Haze			Regional Haze + Red N		
	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
9107	14.9	-1.0	-1.2	-1.1	-0.9	-0.9	-0.6	-0.9	-0.9	-0.6
9116	32.7	-0.5	-0.7	-0.8	-0.5	-0.6	-0.3	-0.5	-0.6	-0.3
9123	51.4	-1.2	-1.9	-2.7	-1.1	-1.7	-2.1	-1.1	-1.7	-2.1
9144	10.6	-0.4	-0.5	-0.5	-0.4	-0.4	-0.1	-0.4	-0.4	-0.1
9150	19.4	-0.3	-0.5	-0.7	-0.3	-0.4	-0.6	-0.3	-0.4	-0.6
9151	9.4	-0.1	-0.2	-0.3	-0.1	-0.1	-0.2	-0.1	-0.1	-0.2
9152	39.7	-1.1	-1.8	-2.8	-1.0	-1.6	-2.3	-1.0	-1.6	-2.3
9153	15.3	-0.5	-0.7	-0.7	-0.5	-0.6	-0.4	-0.5	-0.6	-0.4
9170	23.4	-0.9	-1.5	-2.2	-0.8	-1.3	-1.8	-0.8	-1.3	-1.8
9171	11.7	-1.5	-1.8	-1.7	-1.4	-1.5	-0.8	-1.4	-1.5	-0.8
9172	15.4	0.2	0.8	1.5	0.3	1.1	2.3	0.3	1.1	2.3
9174	38.6	-1.1	-1.6	-2.0	-1.0	-1.4	-1.5	-1.0	-1.4	-1.5
DS04	5.9	-0.2	-0.2	-0.1	-0.2	-0.1	0.1	-0.2	-0.1	0.1
DS09	5.9	-0.4	-0.4	-0.4	-0.3	-0.3	-0.2	-0.3	-0.3	-0.2
DS19	5.9	-0.3	-0.4	-0.4	-0.3	-0.3	-0.1	-0.3	-0.3	-0.1
DS50	6.0	-0.3	-0.5	-0.6	-0.3	-0.4	-0.4	-0.3	-0.4	-0.4
OC02	5.4	0.1	0.3	0.4	0.2	0.4	0.8	0.2	0.4	0.7
OC08	5.4	0.0	0.1	0.2	0.0	0.2	0.4	0.0	0.2	0.4
OC35	5.4	0.1	0.3	0.5	0.1	0.4	0.8	0.1	0.4	0.8
OC79	5.5	-0.1	-0.1	-0.1	0.0	0.1	0.2	0.0	0.1	0.2
VA524S	9.4	-0.9	-1.1	-1.2	-0.8	-1.0	-0.8	-0.8	-1.0	-0.8
VA526S	6.4	-1.0	-1.4	-1.5	-1.0	-1.2	-1.0	-1.0	-1.2	-1.0
VA531S	10.1	-0.3	-0.5	-0.8	-0.2	-0.4	-0.7	-0.2	-0.4	-0.7
VA548S	8.8	-0.5	-0.6	-0.6	-0.5	-0.5	-0.3	-0.5	-0.5	-0.3
VA555S	10.7	-0.3	-0.5	-0.7	-0.3	-0.4	-0.5	-0.3	-0.4	-0.5
VA821S	5.5	-1.9	-2.2	-2.1	-1.8	-1.9	-1.6	-1.8	-1.9	-1.6
WV523S	5.9	-0.3	-0.3	-0.3	-0.2	-0.2	0.0	-0.2	-0.2	0.0
WV531S	11.1	-0.5	-0.6	-0.7	-0.5	-0.5	-0.4	-0.5	-0.5	-0.4
WV547S	6.2	0.4	1.0	1.7	0.6	1.4	2.6	0.6	1.4	2.6

Site ID	Current	Base Case			Regional Haze			Regional Haze + Red N		
	2016	2060	2100	2170	2060	2100	2170	2060	2100	2170
WV548S	8.3	-0.5	-0.6	-0.6	-0.5	-0.4	-0.2	-0.5	-0.4	-0.2
WV769S	10.5	-0.7	-0.8	-0.7	-0.6	-0.6	-0.1	-0.6	-0.6	-0.1
WV770S	11.6	0.2	1.1	2.3	0.4	1.8	3.9	0.4	1.8	3.9
WV771S	10.0	-1.4	-1.7	-1.6	-1.3	-1.3	-0.8	-1.3	-1.3	-0.8
WV785S	8.3	-0.8	-1.2	-1.5	-0.7	-1.0	-1.2	-0.7	-1.0	-1.2
WV788S	9.5	-0.6	-0.9	-1.0	-0.6	-0.7	-0.6	-0.6	-0.7	-0.6
WV796S	12.1	-0.8	-1.3	-1.8	-0.7	-1.1	-1.5	-0.7	-1.1	-1.5

Appendix 6. Target Loads of Sulfur (S) Deposition

Table A5-1. MAGIC modeled target loads of S deposition (meq/m²/yr) for attaining ANC = 30 µeq/L and 50 µeq/L by endpoint years 2060, 2100, and 2170.

Site ID	1860 Stream ANC (µeq/L)	2016 Stream ANC (µeq/L)	2016 Total S Dep (meq/m ² /yr)	Target Load of S for Stream ANC=30 µeq/L in Year			Target Load of S for Stream ANC=50 µeq/L in Year		
				2060	2100	2170	2060	2100	2170
0819003359391	35.8	-14.1	15.2	0.0	0.0	0.0	0.0	0.0	0.0
0819333365729	37.7	21.4	14.7	0.0	0.0	0.0	0.0	0.0	0.0
0819405365852	72.7	25.3	14.3	18.3	18.3	20.7	0.0	0.0	0.0
0819976365378	368.9	341.0	17.8	352.8	352.8	230.1	622.9	350.3	224.8
0820288361949	172.4	132.8	18.7	160.9	160.9	127.5	203.9	143.6	112.8
0820575365023	310.0	288.7	15.0	295.9	295.9	179.5	528.7	292.3	176.2
0820659362857	144.5	120.1	13.0	144.2	144.2	108.7	186.1	126.2	94.0
0821098362008	132.8	108.4	13.3	182.2	182.2	146.4	194.8	152.2	122.0
0821111362567	126.4	69.5	14.5	74.2	74.2	64.3	68.4	53.8	49.0
0821665364328	74.5	-1.8	16.4	6.0	6.0	17.4	0.0	0.0	0.0
0822058362619	99.6	26.6	10.9	37.3	37.3	36.6	15.3	21.9	24.4
0822102358016	58.4	27.3	20.8	17.4	17.4	23.3	0.0	0.0	0.0
0822122357913	58.1	26.6	18.5	19.9	19.9	25.5	0.0	0.0	0.0
0822144357431	67.1	35.5	27.5	36.9	36.9	28.8	0.0	0.0	0.0
0822446357370	59.9	24.3	19.2	11.2	11.2	20.5	0.0	0.0	0.0
0822486357318	52.6	17.5	19.5	0.0	0.0	0.0	0.0	0.0	0.0
0822632361472	86.0	30.9	11.7	43.5	43.5	42.2	11.3	21.2	25.1
0822811357260	58.0	33.0	17.5	30.0	30.0	25.3	0.0	0.0	0.0
0823970361827	189.5	177.2	7.8	129.2	129.2	91.3	242.5	121.7	83.0
0824227362028	140.0	62.0	10.5	59.5	59.5	57.6	52.1	48.3	47.2
0824312360996	73.9	14.9	8.8	19.8	19.8	22.3	0.0	0.8	8.9

Site ID	1860 Stream ANC (µeq/L)	2016 Stream ANC (µeq/L)	2016 Total S Dep (meq/m ² /yr)	Target Load of S for Stream ANC=30 µeq/L in Year			Target Load of S for Stream ANC=50 µeq/L in Year		
				2060	2100	2170	2060	2100	2170
0825384359725	168.1	146.1	12.1	226.9	226.9	136.2	408.0	208.2	122.1
0825869361157	114.7	84.7	6.8	108.0	108.0	83.6	115.0	79.4	60.2
0826140361316	223.2	146.9	16.0	150.3	150.3	149.4	141.2	134.3	133.3
0826540361058	115.0	47.0	14.9	74.2	74.2	71.2	56.0	54.3	53.2
0826728360724	48.2	31.6	5.8	19.3	19.3	18.2	0.0	0.0	0.0
0827495360190	132.9	88.4	5.4	190.6	190.6	110.3	294.7	151.2	87.2
0827728360271	174.0	97.2	14.1	100.5	100.5	98.1	97.5	87.2	84.7
0828146359682	170.8	61.0	22.6	80.5	80.5	73.6	75.2	68.6	63.2
0828261353375	55.4	40.4	17.4	80.6	80.6	57.3	0.0	0.0	0.0
0828670353323	44.3	18.1	35.9	0.0	0.0	0.0	0.0	0.0	0.0
0828817352953	71.6	21.5	18.5	52.2	52.2	52.5	0.0	8.1	16.4
0828920352772	65.7	39.5	16.4	71.4	71.4	60.3	0.0	0.0	9.4
0829067352780	69.7	24.6	20.7	62.5	62.5	62.6	10.3	22.5	27.5
0829079353270	49.4	28.7	18.6	25.5	25.5	30.2	0.0	0.0	0.0
0829160353045	71.3	44.0	20.4	88.3	88.3	73.5	0.0	11.7	25.3
0829184352865	71.2	21.9	17.5	58.7	58.7	59.3	6.1	22.0	27.2
0829194352886	53.9	14.6	13.7	27.1	27.1	29.4	0.0	0.0	0.0
0829321353099	59.6	39.0	12.5	59.3	59.3	50.7	0.0	0.0	2.5
0829630353646	77.2	44.9	34.1	126.0	126.0	89.5	0.0	0.0	4.9
0829670359613	102.6	90.9	8.8	142.1	142.1	87.7	205.5	113.1	69.2
0829674352788	64.7	48.0	19.0	135.5	135.5	92.2	0.0	6.8	15.2
0830494349738	88.4	77.9	18.4	368.3	368.3	209.2	479.3	250.3	141.8
0830849349820	83.7	74.4	18.6	332.9	332.9	189.6	406.6	212.1	121.7
0830946350205	57.9	48.5	16.2	179.4	179.4	104.6	0.0	0.0	1.1
0831036359106	132.3	43.7	16.1	45.8	45.8	44.9	26.3	31.0	34.2
0831139350208	68.3	53.6	9.4	98.2	98.2	71.8	44.3	33.2	28.7

Site ID	1860 Stream ANC (µeq/L)	2016 Stream ANC (µeq/L)	2016 Total S Dep (meq/m ² /yr)	Target Load of S for Stream ANC=30 µeq/L in Year			Target Load of S for Stream ANC=50 µeq/L in Year		
				2060	2100	2170	2060	2100	2170
0831205358440	652.4	622.8	14.0	404.5	404.5	296.2	679.3	402.0	291.2
0831285350075	83.2	73.5	17.7	363.0	363.0	206.6	442.0	227.5	129.9
0831579358839	70.1	32.1	10.6	19.8	19.8	18.6	0.0	0.0	0.0
0831907358024	559.8	482.9	15.3	297.0	297.0	297.0	316.5	285.5	285.5
0832042358247	65.6	50.4	10.6	70.2	70.2	41.5	0.0	0.5	3.7
0835047350176	39.4	29.1	13.1	2.5	2.5	6.7	0.0	0.0	0.0
0835085350173	48.5	37.9	14.7	76.3	76.3	48.0	0.0	0.0	0.0
0839239352738	63.0	37.9	18.1	59.4	59.4	47.2	0.0	0.0	0.0
0839262352702	57.7	42.1	16.8	87.6	87.6	59.2	0.0	0.0	0.0
0839336353542	109.1	101.1	19.5	497.6	497.6	280.4	815.3	420.6	233.9
0839358353530	56.8	31.3	19.7	34.7	34.7	32.3	0.0	0.0	0.0
0839517353661	54.6	38.7	17.7	67.3	67.3	46.4	0.0	0.0	0.0
0839594353679	69.5	44.0	10.1	58.7	58.7	50.7	4.3	15.3	20.3
0839829353633	54.6	23.3	9.5	27.6	27.6	28.8	0.0	0.0	0.0
0839976353481	37.3	7.5	9.6	0.0	0.0	0.0	0.0	0.0	0.0
0840110352961	56.0	20.5	12.3	23.0	23.0	28.7	0.0	0.0	0.0
0840139353542	68.1	26.1	12.3	41.5	41.5	42.5	0.0	0.0	4.0
0840233353666	117.1	32.3	20.0	88.2	88.2	86.6	30.5	46.7	53.0
0840303353155	46.3	-0.6	15.3	3.4	3.4	12.7	0.0	0.0	0.0
0840420353309	78.8	42.3	21.4	91.7	91.7	72.9	0.0	0.0	13.8
0840444353143	52.3	19.7	17.1	21.5	21.5	29.1	0.0	0.0	0.0
0840472353165	55.7	23.9	15.7	28.7	28.7	33.6	0.0	0.0	0.0
0840477353169	67.9	22.0	28.5	15.7	15.7	32.1	0.0	0.0	0.0
0840574353329	77.8	34.7	13.7	61.4	61.4	58.6	4.3	19.7	25.9
0840591352378	68.9	44.7	17.1	78.7	78.7	57.1	0.0	0.0	5.5
0840609353308	88.8	40.3	13.0	72.8	72.8	69.4	30.9	36.8	38.6

Site ID	1860 Stream ANC (µeq/L)	2016 Stream ANC (µeq/L)	2016 Total S Dep (meq/m ² /yr)	Target Load of S for Stream ANC=30 µeq/L in Year			Target Load of S for Stream ANC=50 µeq/L in Year		
				2060	2100	2170	2060	2100	2170
0840675353310	95.2	51.8	15.9	91.7	91.7	73.9	42.8	39.4	39.0
0840745352655	76.0	45.5	15.2	82.5	82.5	68.2	9.0	21.1	27.2
0840802352619	72.6	41.2	10.7	62.9	62.9	59.2	19.5	25.7	27.7
0840876355009	79.2	20.7	14.4	42.0	42.0	41.4	9.1	18.4	21.8
0840886352889	71.7	38.0	14.5	56.7	56.7	50.2	0.0	0.0	9.0
0840893352584	60.8	21.8	16.0	9.3	9.3	17.4	0.0	0.0	0.0
0840999353179	139.1	119.7	10.6	211.2	211.2	166.3	265.2	180.5	139.2
0841126353049	105.6	71.2	16.7	122.3	122.3	99.4	117.7	85.8	72.1
0841405354390	115.2	60.3	11.4	79.1	79.1	77.4	65.2	60.6	59.3
0841965353483	159.6	123.4	6.6	116.4	116.4	92.4	156.8	101.4	77.8
0842048352868	117.6	48.1	25.2	98.8	98.8	91.3	75.8	71.9	68.3
0843145352310	186.2	165.9	7.9	133.7	133.7	122.9	179.3	121.4	107.6
0843377352707	180.1	176.7	5.2	284.8	284.8	170.4	499.7	273.6	161.3
0843873352029	198.1	137.4	18.6	128.5	128.5	126.7	133.5	114.2	111.8
0844151352181	98.9	50.1	13.8	63.6	63.6	54.4	38.3	36.1	34.5
0844273352649	308.5	219.5	15.8	202.6	202.6	202.5	191.6	188.1	188.0
0844278351285	80.4	26.9	14.8	48.7	48.7	47.8	3.5	19.1	25.1
0844525350546	149.2	47.2	22.8	93.9	93.9	91.4	71.5	73.2	74.4
0844889349896	101.1	65.8	10.9	85.5	85.5	74.0	73.3	58.8	52.1
0844895352737	79.3	62.5	12.6	127.6	127.6	77.6	110.4	60.9	39.0
0845569351056	361.6	343.4	12.0	270.9	270.9	240.6	448.2	262.1	226.9
0845716351232	101.2	27.8	9.7	29.1	29.1	28.6	0.0	4.6	10.7
0845774349971	176.6	108.9	28.3	174.0	174.0	166.7	182.3	152.5	144.3
0845832350276	138.5	71.3	20.4	131.7	131.7	122.1	118.5	105.8	98.5
0845920348656	72.6	44.0	8.5	55.3	55.3	51.1	17.8	22.3	24.2
0846002348667	76.3	52.1	7.6	65.0	65.0	56.6	34.3	31.4	30.2

Site ID	1860 Stream ANC (µeq/L)	2016 Stream ANC (µeq/L)	2016 Total S Dep (meq/m ² /yr)	Target Load of S for Stream ANC=30 µeq/L in Year			Target Load of S for Stream ANC=50 µeq/L in Year		
				2060	2100	2170	2060	2100	2170
0846071350417	573.9	514.7	14.4	407.0	407.0	407.0	392.6	391.2	391.2
0846340349016	98.6	58.0	11.7	91.5	91.5	86.2	70.0	62.4	59.9
0846480349362	181.7	59.2	36.6	174.5	174.5	173.0	155.7	151.3	150.2
0846837350065	451.1	276.8	31.0	286.5	286.5	285.9	273.0	272.4	271.8
22002	52.0	21.5	9.9	22.3	22.3	24.8	0.0	0.0	0.0
23051.5	136.4	66.0	14.7	60.2	60.2	53.5	54.3	46.5	42.8
23065	87.6	38.0	8.8	40.4	40.4	38.2	14.6	20.0	21.9
23066	76.4	49.8	10.8	55.4	55.4	41.6	15.2	16.8	18.0
23073	158.9	141.5	13.3	454.0	454.0	294.5	709.5	420.5	267.3
23079	274.1	254.7	6.2	615.6	615.6	347.4	1150.4	611.9	345.5
23088.5	64.3	0.9	15.3	4.9	4.9	16.2	0.0	0.0	0.0
5502	134.6	87.9	15.5	108.0	108.0	89.4	117.6	87.1	72.0
5532	90.0	3.0	18.8	28.6	28.6	31.5	0.0	3.4	14.1
5541	161.3	87.3	28.0	148.9	148.9	133.3	153.3	126.0	113.5
5550	77.8	-8.3	28.6	9.2	9.2	25.5	0.0	0.0	0.0
5568	284.1	238.0	15.7	140.1	140.1	114.0	230.0	136.4	105.7
6512	45.1	2.2	36.2	0.0	0.0	0.0	0.0	0.0	0.0
6515	47.7	13.5	14.4	0.0	0.0	0.0	0.0	0.0	0.0
6519	73.5	56.0	31.5	200.1	200.1	107.2	99.3	47.6	24.5
6531	117.7	90.1	25.7	130.1	130.1	75.0	195.2	100.6	56.5
6573	46.3	-22.1	52.3	0.0	0.0	0.0	0.0	0.0	0.0
6577	77.5	25.3	12.7	23.1	23.1	24.1	0.0	0.0	4.0
7000	159.6	67.1	16.0	67.7	67.7	61.9	63.1	56.5	52.1
7002	101.6	66.7	11.7	64.2	64.2	45.9	59.9	39.1	30.4
8006	32.7	-15.5	34.7	0.0	0.0	0.0	0.0	0.0	0.0
8024	49.6	-30.2	74.5	0.0	0.0	0.0	0.0	0.0	0.0

Site ID	1860 Stream ANC (µeq/L)	2016 Stream ANC (µeq/L)	2016 Total S Dep (meq/m ² /yr)	Target Load of S for Stream ANC=30 µeq/L in Year			Target Load of S for Stream ANC=50 µeq/L in Year		
				2060	2100	2170	2060	2100	2170
8068	64.9	-8.5	47.3	0.0	0.0	0.0	0.0	0.0	0.0
8082	97.1	64.3	26.6	123.5	123.5	90.1	114.2	75.6	56.3
8084	108.8	17.7	30.0	8.7	8.7	20.3	0.0	0.0	0.9
8094	50.3	19.1	28.1	0.0	0.0	0.0	0.0	0.0	0.0
8129	29.2	-16.0	39.0	0.0	0.0	0.0	0.0	0.0	0.0
9011	66.8	22.4	25.5	7.5	7.5	17.9	0.0	0.0	0.0
9031	85.1	50.5	11.6	52.7	52.7	43.0	23.8	22.7	22.1
9041	82.9	52.0	17.0	80.1	80.1	53.4	22.5	16.6	14.9
9042	68.5	15.3	23.2	0.0	0.0	4.1	0.0	0.0	0.0
9050	126.9	49.6	35.7	83.8	83.8	68.5	30.1	31.7	35.3
9055	99.9	43.8	27.5	72.9	72.9	56.9	0.0	6.2	14.5
9063	72.6	24.2	22.3	12.1	12.1	18.6	0.0	0.0	0.0
9073	107.0	46.7	24.7	55.0	55.0	45.3	6.9	15.6	20.4
9100	149.6	99.4	9.8	82.0	82.0	69.8	90.1	68.4	57.9
9104	64.0	-22.8	23.7	0.0	0.0	0.0	0.0	0.0	0.0
9105	79.3	22.2	24.0	25.3	25.3	29.4	0.0	0.0	0.0
9107	105.8	-8.6	21.0	19.4	19.4	28.4	0.0	0.0	13.6
9116	60.6	-8.3	11.2	12.2	12.2	16.0	0.0	0.0	0.0
9123	105.4	74.7	12.5	85.3	85.3	65.7	88.4	61.6	48.0
9144	116.1	67.0	10.1	53.1	53.1	44.9	47.5	37.6	33.0
9150	65.0	-6.9	19.3	0.0	0.0	12.5	0.0	0.0	0.0
9151	53.0	-25.3	21.8	0.0	0.0	0.0	0.0	0.0	0.0
9152	90.4	48.0	18.8	64.2	64.2	50.5	18.6	21.8	23.0
9153	43.8	-49.8	17.1	0.0	0.0	0.0	0.0	0.0	0.0
9170	87.6	35.2	22.0	36.3	36.3	32.5	0.0	0.0	7.0
9171	188.2	110.3	21.0	92.7	92.7	84.1	105.4	80.6	73.7

Site ID	1860 Stream ANC (µeq/L)	2016 Stream ANC (µeq/L)	2016 Total S Dep (meq/m ² /yr)	Target Load of S for Stream ANC=30 µeq/L in Year			Target Load of S for Stream ANC=50 µeq/L in Year		
				2060	2100	2170	2060	2100	2170
9172	100.5	34.5	9.2	39.1	39.1	38.3	22.7	25.7	26.7
9174	74.9	20.9	11.3	26.0	26.0	26.2	0.0	0.7	8.4
DS04	52.6	-65.0	33.9	0.0	0.0	0.0	0.0	0.0	0.0
DS09	49.8	-58.7	42.0	0.0	0.0	0.0	0.0	0.0	0.0
DS19	65.5	-35.8	38.5	0.0	0.0	0.0	0.0	0.0	0.0
DS50	49.0	-27.9	47.9	0.0	0.0	0.0	0.0	0.0	0.0
OC02	73.0	-55.9	29.7	0.0	0.0	9.5	0.0	0.0	0.0
OC08	46.5	-75.1	30.7	0.0	0.0	0.0	0.0	0.0	0.0
OC35	83.7	-58.8	34.0	4.1	4.1	29.7	0.0	0.0	4.9
OC79	103.0	10.2	35.0	22.0	22.0	40.1	0.0	0.0	5.4
VA524S	102.0	-13.6	40.5	0.5	0.5	26.6	0.0	0.0	0.0
VA526S	198.8	100.6	40.8	115.2	115.2	96.5	133.7	94.4	83.0
VA531S	112.6	65.5	59.0	180.8	180.8	110.5	173.2	97.2	61.3
VA548S	125.5	20.6	21.2	46.1	46.1	48.3	8.7	26.0	33.5
VA555S	61.4	17.9	36.9	0.0	0.0	0.0	0.0	0.0	0.0
VA821S	171.5	78.6	32.0	47.9	47.9	50.2	30.6	32.9	39.8
WV523S	50.7	-39.7	27.3	0.0	0.0	0.0	0.0	0.0	0.0
WV531S	59.9	-47.7	29.7	0.0	0.0	0.0	0.0	0.0	0.0
WV547S	217.2	70.3	32.7	166.0	166.0	161.9	155.6	146.4	143.4
WV548S	92.2	-26.1	35.6	0.0	0.0	12.3	0.0	0.0	0.0
WV769S	154.2	33.1	29.4	91.1	91.1	87.3	59.2	66.4	68.7
WV770S	223.0	113.0	26.5	161.2	161.2	152.4	163.5	144.8	136.6
WV771S	226.7	126.5	33.3	161.6	161.6	140.7	185.9	145.5	126.1
WV785S	100.7	-60.0	52.0	0.0	0.0	0.0	0.0	0.0	0.0
WV788S	93.1	-3.0	39.7	0.0	0.0	23.3	0.0	0.0	0.0
WV796S	110.8	42.0	47.0	59.5	59.5	48.7	0.0	3.1	14.5

Appendix 7. Continuous Regression Models for Predicting Acid Neutralizing Capacity (ANC)

Northern ANC model description

$r^2 = 0.54$
 $p\text{-value} < 0.001$
 $RMSE = 25.17$
 $MAE = 17$

Coefficients:

	Estimate	Std. Error	t-value	p-value
(Intercept)	4.177e+02	1.054e+02	3.962	8.95e-05
lat	-8.568e+00	2.729e+00	-3.139	0.00183
fac	3.069e-04	1.338e-04	2.295	0.02233
conmix	-6.683e+01	9.870e+00	-6.771	5.16e-11
lithsil	-5.232e+01	3.333e+00	-15.699	< 2e-16
sand	-5.436e+01	1.078e+01	-5.043	7.24e-07
ab90grow	1.063e-02	2.565e-03	4.143	4.26e-05

Southern ANC model description

$r^2 = 0.22$
 $p\text{-value} < 0.001$
 $RMSE = 22.75$
 $MAE = 16$

Coefficients:

	Estimate	Std. Error	t-value	p-value
(Intercept)	1.569e+01	9.854e+00	1.592	0.111568
fac	7.912e-05	2.150e-05	3.679	0.000245
pptann	-9.282e-03	3.415e-03	-2.718	0.006663
bfi	9.266e-01	1.278e-01	7.249	7.82e-13
decmix	1.412e+01	5.200e+00	2.715	0.006729
litharg	-4.630e+00	1.886e+00	-2.455	0.014223
lithmaf	2.181e+01	7.322e+00	2.979	0.002953
lithsil	-1.262e+01	2.030e+00	-6.218	7.10e-10
sand	-4.743e+01	8.321e+00	-5.701	1.52e-08
hydb	-1.615e-01	3.060e-02	-5.277	1.58e-07
pered	-2.550e-01	7.785e-02	-3.275	0.001088
vdcontday	2.488e-01	2.922e-02	8.515	< 2e-16

Appendix 8. Continuous Regression Models for Predicting Base Cation Weathering (BC_w)

Landscape BC_w model description

$r^2 = 0.35$
p-value < 0.001
RMSE = 49.31
MAE = 28

Coefficients:

	Estimate	Std. Error	t-value	p-value
(Intercept)	125.345102	118.602837	1.057	0.292081
twi	-34.054319	10.621775	-3.206	0.001608
sdep0002	0.545094	0.148259	3.677	0.000317
lithsil	-43.175189	9.039312	-4.776	3.84e-06
soilph	53.629565	19.632800	2.732	0.006968
perspd	-80.391290	23.456694	-3.427	0.000765
ab90grow	0.037051	0.005016	7.387	6.46e-12

Landscape + water chemistry BC_w model description

$r^2 = 0.96$
p-value < 0.001
RMSE = 12.3
MAE = 7

Coefficients:

	Estimate	Std. Error	t-value	p-value
(Intercept)	32.644127	29.721535	1.098	0.273622
BC _{w, FB}	0.825809	0.016359	50.482	< 2e-16
twi	-0.938235	2.736494	-0.343	0.732130
sdep0002	0.005163	0.038594	0.134	0.893739
lithsil	-2.421798	2.400703	-1.009	0.314519
soilph	-7.122004	5.055838	-1.409	0.160770
perspd	4.771978	6.104679	0.782	0.435489
ab90grow	0.005450	0.001402	3.887	0.000146