CHAPTER 8.

Climate Change Impacts on Forest Soil Critical Acid Loads and Exceedances at a National Scale

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INTRODUCTION

Federal agencies are currently developing guidelines for forest soil critical acid loads across the United States. A critical acid load is defined as the amount of acid deposition (usually expressed on an annual basis) that an ecosystem can absorb. Traditionally, an ecosystem is considered to be at risk for health impairment when the critical acid load exceeds a level known to impair forest health. The excess over the critical acid load is termed the *exceedance*, and the larger the exceedance, the greater the risk of ecosystem damage. This definition of critical acid load applies to a single, long-term pollutant exposure. These guidelines are often used to establish regulations designed to maintain acidic deposition, e.g., nitrogen and sulfur, inputs below the level shown to exceed an ecosystem's critical acid load. The traditional definition for a critical acid load generally assumes that the ecosystem is in a steady state condition, i.e., no major changes in the factors that regulate the ecosystem's ability to absorb acids. Unfortunately, climate change is altering weather patterns and, thus, impacting the factors that regulate critical acid load limits. This chapter explores which factors associated with establishing forest soil critical acid load limits will most likely be influenced by climate change, and how these changes might impact forest soil critical acid load limits across the United States. In New England, for example, base cation weathering could increase with global warming, along with nitrogen uptake as a function of increased forest growth. Nationally, a moderate 20-percent increase in base cation weathering and nitrogen uptake would result in at least a 30.5-percent decrease in the amount of forest soil area that exceeded the critical acid load limit and at least a 64.4-percent decrease in the amount of high exceedance area. While these results are encouraging, they do not account for other negative potential forest health risks associated with climate change such as elevated fire, insect, or disease risk. Additional study is needed before the full impact of climate change on forest health can be assessed.

Airborne nitrogen (N) and sulfur (S) from industrial pollution and automobile exhausts have been deposited across Europe and the Northeastern United States for over 70 years in the form of acid rain. Heavily polluted areas can receive over 50 kg N ha^{-1} each year (Holland and others 2005). The environmental impacts of air pollutants have been studied since N and S were first suspected to cause forest damage and decline across the region in the mid-1980s. High pollutant levels and forest mortality can lead to mobilization of soil aluminum (Al^{3+}) and nitrate (NO_3^-) (Berg 1986, Cronan and Schofield 1979, Johnson and others 1994) and subsequent increases in stream Al and NO_3 concentrations. Increased Al and NO_3 stream concentrations can have negative health impacts on fish populations and human water supplies (Baker and others 1996). High forest soil acidity can also cause aluminum toxicity in roots (Shortle and Smith

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1988), foliar nutrient imbalances (Cronan and Grigal 1995, Zoettl and Huettl 1986), reduced tree cold tolerance (Sheppard 1994), and tree freezing injury (DeHayes and others 1992). Each of these stressors can lead to tree mortality (Aber and others 1989, McNulty and others 2007).

Traditionally, an ecosystem is considered to be at risk for health impairment when its critical acid load from deposition (and rarely from rocks) exceeds the amount of acid that the ecosystem can absorb. Often, 200 eq [equivalents or moles of charge (Aherne 2008)] ha^{-1} yr^{-1} is used as a standard known to impair forest health. Acidic deposition in excess of the critical acid load is termed the acidic exceedance, and the larger the acidic exceedance, the greater the risk of ecosystem damage. This definition of critical acid load applies to a single, long-term pollutant exposure. However, a static critical acid load level may not accurately assess ecosystem risk to damage when an ecosystem is subjected to multiple, episodic environmental stresses. If multiple stress impacts (drought, insects, wildfire) are included in critical acid load assessments, the critical acid load may need to be lowered in many areas to maintain long-term ecosystem health.

Various methods have been developed to assess the ecosystem soil's critical acid load. One of the most common methods for determining an ecosystem's critical acid load is the use of a simple mass balance equation (SMBE) that uses static soil, climate, vegetation, and pollutant deposition data to estimate a soil's critical acid load. Previous SMBEs have been used to estimate forest soil critical acid loads and exceedances at a 1-km^2 resolution across the conterminous United States (McNulty and others 2007). In this chapter, an SMBE is modified to examine how climate change could alter an ecosystem's critical acid load and potential for acid soil exceedance.

Climate Change Impacts on Critical Acid Loads

Climate change is a generic term used to define a host of changing environmental conditions associated with the atmospheric increase of greenhouse gases and global warming. Climate change is characterized by both climatic shifts and increased climate variability. Both inter-decadal shifts in climate and inter-annual climate variability can influence the critical acid load of forest soils. Each of these impacts is examined below.

Short- and Long-Term Droughts

Water is one of the principle determinants of ecosystem type. Average annual precipitation in temperate forests ranges from 50 to 250 cm per year. Deserts, scrubland, and woodlands receive between 0 and 125 cm of precipitation per year (Whittaker 1970). Millennia of plant competition have favored vegetative species that best adapt to limited resources (including water). Short-term, i.e., < 2 years, drought can reduce ecosystem productivity (Hanson and Weltzin 2000), leaf longevity in deciduous species (Jonasson and others 1997), and leaf area (Gholz and others 1990). These factors reduce biological demand for nitrogen which can alter soil critical acid loads. Under short-term, i.e., < 2 years, extreme drought, reduced soil moisture can cause reduced nitrogen mineralization and nitrification that then result in reduced ammonium and nitrate availability. These conditions would not impact critical acid load in the short term if both nitrogen demand and supply are reduced. However, nitrogen will continue to accumulate in the ecosystem during the drought. A nitrate pulse could occur following a drought if nitrogen mineralization and nitrification rates respond to available water before plant demand for nitrogen increases.

Long-term, i.e., > 2 years, droughts can cause additional ecosystem disruptions and therefore have the potential to significantly lower forest soil critical acid load levels. Long-term droughts have all of the characteristics of short-term drought plus the potential for tree mortality due to water stress (Kloeppel and others 2003), increased insect outbreak potential (Mattson and Haack 1987), and increased fire risk (Flannigan and Wotton 2001). As with short-term drought, long-term drought may reduce biological nitrogen demand and supply. Additionally, the potential for terrestrial vegetation mortality could lead to a significant decrease in biological nitrogen uptake. If tree mortality is severe, a large nitrate pulse could occur following the drought, similar to the nitrate pulse observed following forest harvesting (Vitousek and Matson 1985).

The forest soil critical acid load may be significantly reduced for several years after drought-induced forest mortality, because new growth cannot fully utilize existing water, light, and nutrients. For example, around Mt. Mitchell in the Southern Appalachian Mountains a combination of drought, increased air temperature, and insects likely caused the mortality of mature high elevation red spruce (*Picea rubens*) trees in 2001 (McNulty and Boggs 2010). The forest soil critical acid load for this area was reduced until new growth could fill in gap openings and increase biological nitrogen uptake.

Climate Change Shifts in Precipitation

Both short- and long-term droughts are transient weather events. However, climate change is a permanent shift in the amount and timing of precipitation for a region. Changes in tree species distributions, nutrient cycling, and water flow are all likely with climatic shifts. Reductions in precipitation would cause a shift toward more open, drought-tolerant woodlands (Hansen and others 2001). As tree density decreases, nitrogen demand and uptake by vegetation decreases. Therefore, a forest soil critical acid load for an ecosystem receiving less precipitation could decrease. Conversely, the forest soil critical acid load could increase if climate change results in an increase in precipitation, along with a shift toward more dense forests with higher nitrogen demands.

Permanent precipitation change-induced forest species shifts can also change the nitrogen cycle. Mesic tree species tend to be more nitrogen demanding (Watmough and others 2004). Therefore, increased precipitation could gradually shift a forest toward a higher forest soil critical acid load, while reductions in precipitation could have a negative impact on nitrogen uptake and soil critical acid loads.

Climate Change Shifts in Air Temperature

During the next century, substantial changes are expected to occur in a variety of environmental variables including temperature. The magnitude of these changes is expected to vary temporally and spatially. The Intergovernmental Panel on Climate Change (IPCC) concluded that average global surface temperature is projected to increase by 1.8 C° to 3.6 C° above 2000 levels by 2100 (IPCC 2007).

Biological processes accelerate as air temperature increases. Increases in tree respiration and metabolism can shorten leaf retention time as temperature increases. Litter decomposition, soil nitrogen mineralization, and soil nitrification also increase with increasing temperature. Increases in both nitrogen demand and supply can offset each other, so the forest soil critical acid load may not change. In cooler regions, increases in air temperature may increase forest productivity and therefore nitrogen uptake. However, in warmer climates air temperature may be at (or above) the optimal levels for forest growth. Additional warming would decrease tree growth and reduce nitrogen uptake. If tree nitrogen demand does not keep pace with nitrogen availability, then the forest soil critical acid load could decrease with increasing air temperature.

METHODS

Assessing Climate Change Impact on Critical Acid Loads Using a Simple Mass Balance Equation

Climate change can impact many aspects of ecosystem function, e.g., insect outbreaks, wildfire occurrence, and susceptibility. While some of these potential impacts cannot be represented in an SMBE, some important aspects of a critical acid load that may be impacted can be assessed using the SMBE approach. The complete methodology and databases used to produce the assessment of historic acidic deposition impacts on forest soil critical acid loading are available in McNulty and others (2007). Several databases (table 8.1) were used to run the SMBE model, and all operations occurred in a geographic information system (GIS). The soil database was used as the base layer for the GIS operations, and it had a spatial resolution of 1 km². All other databases used in the SMBE model were aligned to the soil database and rescaled to 1 km². Critical acid loads are calculated using the following SMBE:

$$CAL(S{+}N) = BC_{dep} - Cl_{dep} + BC_w - BC_u + N_i + N_u + N_{de} - ANC_{le,crit} \qquad (1)$$

where

$CAL(S{+}N)$ = the forest soil critical acid load for S and N

BC_{dep} = base cation [i.e., calcium (Ca) + potassium (K) + magnesium (Mg) + sodium (Na)] deposition

Table 8.1—Descriptions of input datasets used to run the simple mass balance equation (SMBE) model. All operations occurred in a geographic information system

Data set	Source	Temporal scale	Original display scale	Original spatial scale
Dry deposition	U.S. EPA (2007)	1994-2000	NA	NA
Forest type	USDA Forest Service (unpublished)	2002-2003	< 1:2,000,000	250-m
Runoff	Gebert and others (1987)	1951-1980	1:7,500,000	1-m
Soils	State Soil Geographic (STATSGO) database (USDA NRCS 1995)	NA	1:250,000	6.25-km
Wet deposition	Grimm and Lynch (2004)	1994-2000	NA	330-m or 1-km
	National Atmospheric Deposition Program (NADP) annual isopleths maps (NADP 2005)	1994-2000	NA	2.5-km
Wilderness area	National Atlas (National Atlas of the United States 2005)	NA	1:2,000,000	NA

NA = Not applicable.

Cl_{dep} = chloride deposition

BC_w = base cation weathering

BC_u = uptake of base cations (i.e., Ca + K + Mg) in trees

N_i = nitrogen immobilization

N_u = uptake of nitrogen in trees

N_{de} = denitrification

$ANC_{le,crit}$ = forest soil acid neutralizing capacity of CAL leaching (Gregor and others 2004).

Each parameter in the SMBE was represented by a GIS layer. Critical acid loads for the conterminous United States are shown in figure 8.1.

Critical acid load exceedance (eq ha^{-1} yr^{-1}) was calculated using the following equation:

$$Ex(S+N_{dep}) = S+N_{dep} - CAL(S+N) \qquad (2)$$

where

Ex = exceedance of the forest soil critical N and S load

$S+N_{dep}$ = the deposition of S plus N

$CAL(S+N)$ = the forest soil critical load of S plus N (Gregor and others 2004).

Higher *Ex* values reflect greater exceedance of acidic deposition above the level associated with an increased likelihood of environmental harm (fig. 8.2).

Base cation weathering has the largest influence on SMBE estimates of a critical acid load (Li and McNulty 2007). The most recent IPCC report suggests that a global warming may increase the earth's surface temperature by almost 4 C° by the end of the 21st century (IPCC 2007). For this examination of critical acid load sensitivity to changes in climate, we re-ran the equations that estimated base cation weathering by adding 4 C° to the average annual air temperature values across the conterminous United States.

As previously discussed, forest productivity may increase (cooler regions) or decrease (warmer regions) with a 4 C° increase in air temperature. To simulate this variability, we developed another scenario in which forest productivity (and therefore nitrogen uptake) was increased and decreased by 20 percent from historic levels. The combinations of increased base cation weathering and nitrogen uptake and decreased nitrogen uptake were entered into the SMBE to examine climate change impacts on critical acid loading and exceedances across the conterminous United States at a 1-km^2 scale.

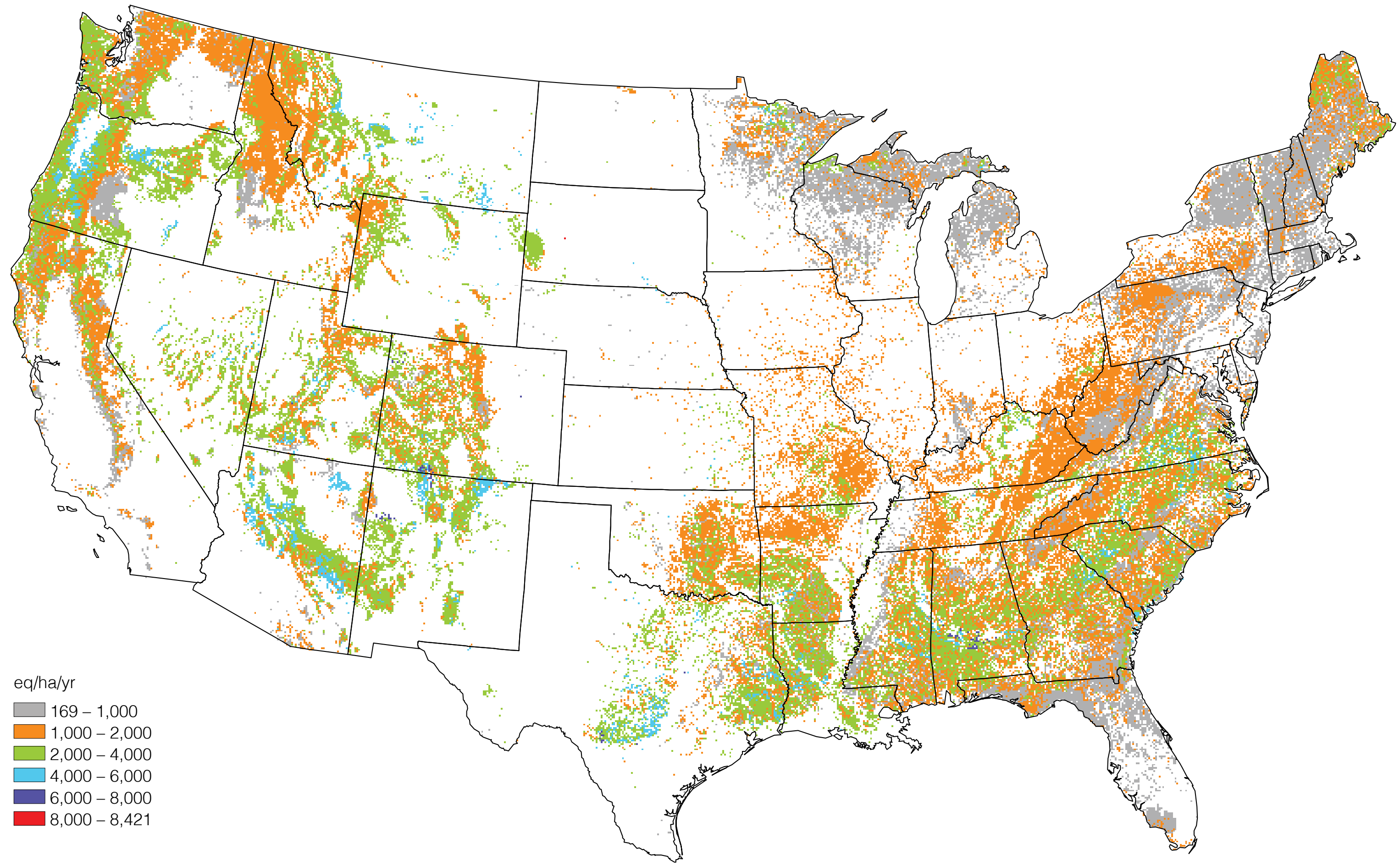

Figure 8.1—Critical loads of acidity in forest soils, baseline. (Data sources: EPA 2007, Gebert and others 1987, Grimm and Lynch 2004, National Atlas of the United States 2005, NADP 2005, and USDA NRCS 1995)

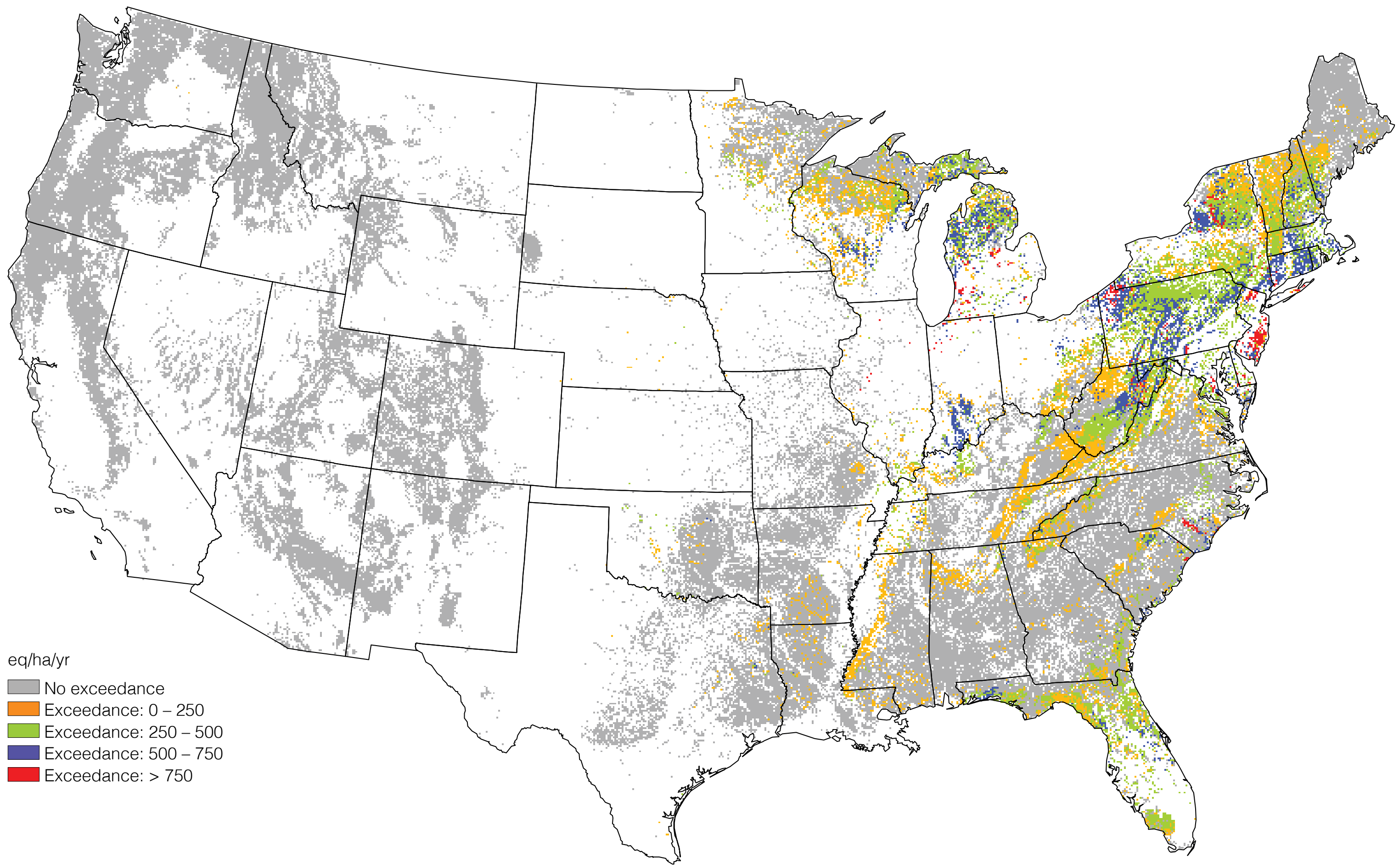

Figure 8.2—Exceedance of critical loads of acidity in forest soils, baseline. (Data sources: EPA 2007, Gebert and others 1987, Grimm and Lynch 2004, National Atlas of the United States 2005, NADP 2005, and USDA NRCS 1995)

RESULTS

A 4 C° increase in air temperature resulted in a 20-percent increase in base cation weathering. As expected based on the SMBE sensitivity analysis (Li and McNulty 2007), a 20-percent increase in base cation weathering and nitrogen uptake had a significant impact on both the forest soil critical acid loads level (fig. 8.3) and the amount of exceedance across the conterminous United States (fig. 8.4). The total percentage of forest area that was in exceedance of the critical acid load decreased from 22 percent in the baseline scenario to 16.6 percent in the increased base cation weathering scenario. This represents a 24.5-percent decrease in forest area impacted by acidic deposition. More significantly, the forest areas that were most impacted (≥ 500 eq acid l^{-1}) experienced an even larger reduction in impacted area, dropping from 4.5 percent to 2.0 percent of the total forest area (a 55.6-percent reduction) under the baseline and climate change scenarios, respectively (tables 8.2 and 8.3).

Conversely, increases and decreases in nitrogen uptake associated with changes in forest growth had a relatively small impact on the total percentage of forest area with soils that exceeded their critical load limits. A 20-percent increase in N uptake reduced the total area in exceedance of the forest soil critical acid load by 0.5 percent (22.0 percent to 21.9 percent of total area) and had no impact on the most impacted forest area. In comparison, 20-percent and 40-percent decreases in nitrogen uptake that would be associated with reductions in forest growth increased the amount of total and most impacted forest area with soils in exceedance of the critical acid load (tables 8.2 and 8.3).

The combination of increased nitrogen uptake and increased base cation weathering did not significantly reduce the amount of forest area in exceedance of the critical acid load beyond the reduction due to increased base cation weathering alone. When compared to the baseline, the increased weathering and 20-percent decreased nitrogen uptake scenario reduced the total forest area impacted by acid loading by 24.1 percent and reduced highly impacted forest area by 53.3 percent. Without the addition of increased nitrogen uptake, the increased weathering scenario alone reduced the total forest area impacted by 24.5 percent and reduced highly impacted forest area by 55.6 percent (table 8.3).

Although reductions in forest growth and nitrogen uptake are likely under a changing climate in some areas of the United States, these areas are more likely to be limited to the warmer, i.e., southern, regions of the country. The Northern United States could experience increased forest growth and nitrogen uptake associated with longer growing seasons. The majority of forest soil areas currently in exceedance of their critical acid load are located in the Northern United States (fig. 8.2). Therefore it is unlikely that increased weathering and reduced N uptake (associated with reductions in productivity) will be occurring in areas where most of the exceedances occur, i.e., Northeastern United States.

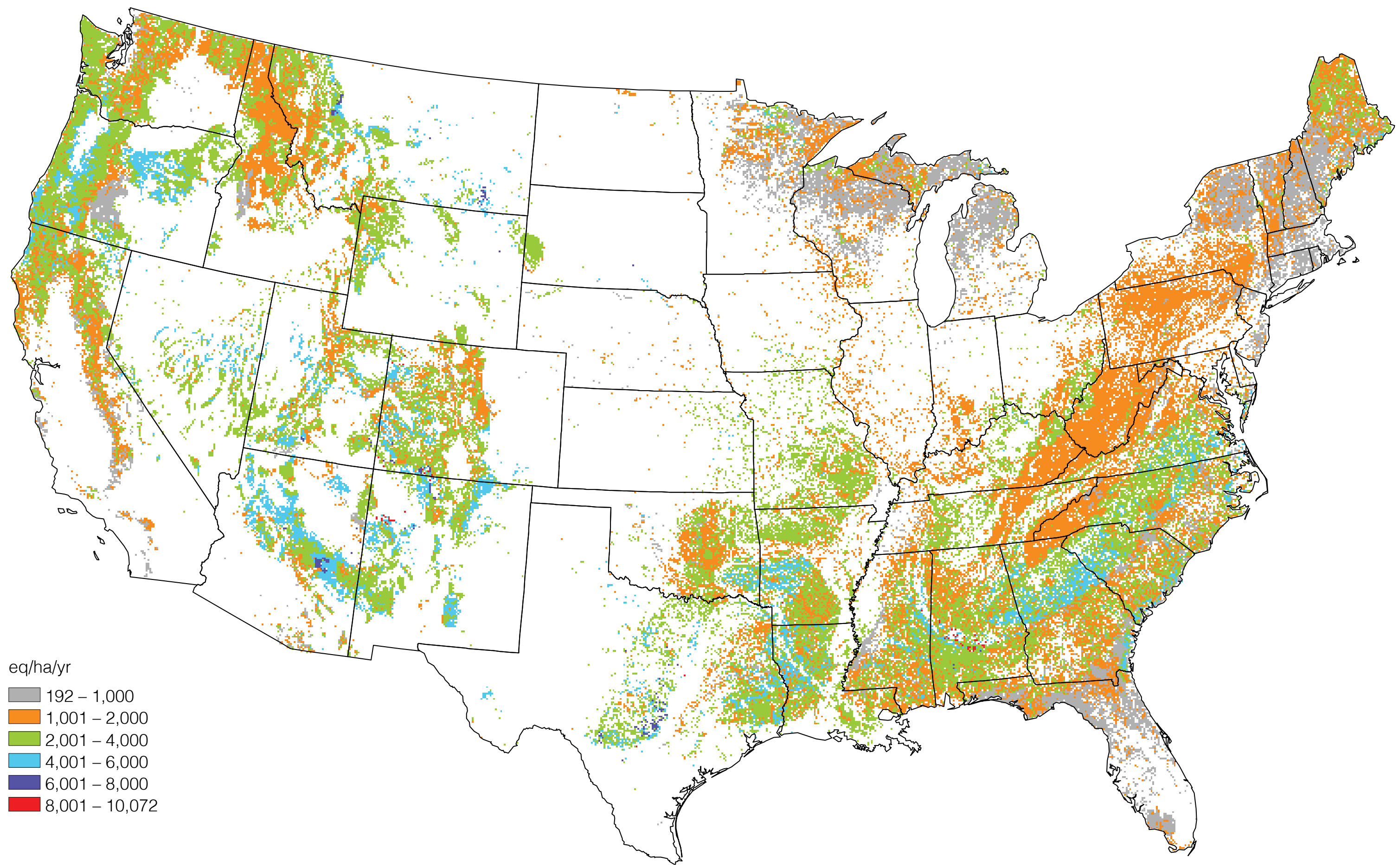

Figure 8.3—Critical loads of acidity in forest soils, base cation weathering 20-percent increase and nitrogen uptake 20-percent increase. (Data sources: EPA 2007, Gebert and others 1987, Grimm and Lynch 2004, National Atlas of the United States 2005, NADP 2005, and USDA NRCS 1995)

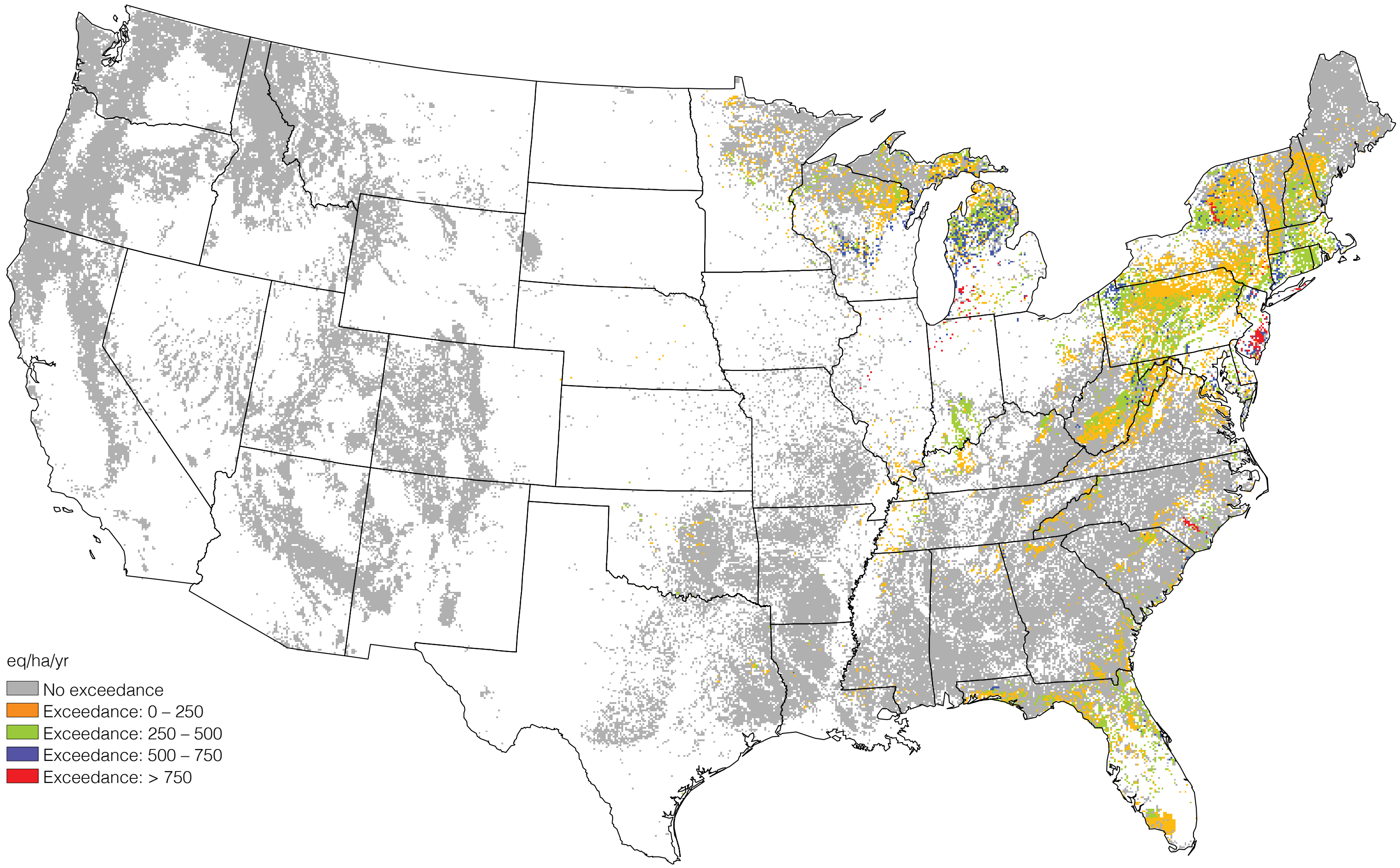

Figure 8.4—Exceedance of critical loads of acidity in forest soils, base cation weathering 20-percent increase and nitrogen uptake 20-percent increase. (Data sources: EPA 2007, Gebert and others 1987, Grimm and Lynch 2004, National Atlas of the United States 2005, NADP 2005, and USDA NRCS 1995)

Table 8.2—Percent of entire conterminous United States forest area in exceedance, and percent of United States forest area in exceedance of 500 eq ha^{-1} yr^{-1}

Scenario	Baseline	BCW20%i	N20%i	N20%d	N40%d	BCW20%i N20%i	BCW20%i N20%d	BCW20%i N40%d
Percent of forested area impacted by acidic deposition	22.0	16.6	21.9	23.2	24.4	15.3	16.7	18.2
Percent of forest area in exceedance ≥ 500 eq/ha/yr	4.5	2.0	4.5	5.8	7.1	1.6	2.1	2.9

BCW = base cation weathering; N = nitrogen uptake; d = decrease; i = increase.

Table 8.3—Percent change of conterminous United States forest area in exceedance and percent change of United States forest area in exceedance of 500 eq ha^{-1} yr^{-1} when comparing simple mass balance equation (SMBE) scenarios to baseline conditions

Scenario	BCW20%i	Na20%i	N20%d	N40%d	BCW20%i N20%i	BCW20%i N20%d	BCW20%i N40%d
Percent change, forest area impacted by acidic deposition	-24.5	-0.5	5.5	10.9	-30.5	-24.1	-17.3
Percent change, forest area in exceedance ≥ 500 eq/ha/yr	-55.6	0.0	28.9	57.8%	-64.4%	-53.3	-25.6
Forest area impacted	Reduction	Reduction	Increase	Increase	Reduction	Reduction	Reduction

BCW = base cation weathering; N = nitrogen uptake; d = decrease; i = increase.

CONCLUSIONS

Climate change is expected to negatively impact forest ecosystems in several ways during this century. However, the exacerbation of forest soils affected by acidic deposition may not be among those negative impacts. The results of this SMBE suggest that those soils most likely to be in exceedance of their critical acid load levels, e.g., in New England forests, may also be the most likely to benefit from the warming associated with climate change. Increases in both nitrogen uptake and base cation weathering are predicted in this region of the country.

The increase in weathering rates would be particularly important for increasing the region's critical acid load capacity. This study suggests that a major reduction in the area representing the most seriously impacted forest soils could occur. While this is potentially good news for ecosystem management, other aspects of climate change are not accounted for by the simple mass balance equation approach to critical acid load determination. Potential increases in insect outbreaks, hurricane intensity, wildfires, and changing patterns of ice storms could all reduce forest productivity and therefore nitrogen uptake. These conditions would reduce the buffering capacity of the ecosystem and make it more likely that the ecosystem would be in exceedance of its critical acid load, so caution should be used when interpreting these results.

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