



A conceptual framework: Redefining forest soil's critical acid loads under a changing climate

Steven G. McNulty*, Johnny L. Boggs

USDA Forest Service, Eastern Forests Environmental Assessment Threats Center, Southern Global Change Program, 920 Main Campus Dr. Suite 300, Raleigh, NC 27606, USA
Forests appear much less able to tolerate elevated acid loading when subjected to multiple stresses, thus future assessment of CALs and exceedances need to address the dynamic nature of multiple environmental stress if improvements in identifying areas of impaired forest health are to be achieved.

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ABSTRACT

Federal agencies of several nations have or are currently developing guidelines for critical forest soil acid loads. These guidelines are used to establish regulations designed to maintain atmospheric acid inputs below levels shown to damage forests and streams. Traditionally, when the critical soil acid load exceeds the amount of acid that the ecosystem can absorb, it is believed to potentially impair forest health. The excess over the critical soil acid load is termed the exceedance, and the larger the exceedance, the greater the risk of ecosystem damage. This definition of critical soil acid load applies to exposure of the soil to a single, long-term pollutant (i.e., acidic deposition). However, ecosystems can be simultaneously under multiple ecosystem stresses and a single critical soil acid load level may not accurately reflect ecosystem health risk when subjected to multiple, episodic environmental stress. For example, the Appalachian Mountains of western North Carolina receive some of the highest rates of acidic deposition in the eastern United States, but these levels are considered to be below the critical acid load (CAL) that would cause forest damage. However, the area experienced a moderate three-year drought from 1999 to 2002, and in 2001 red spruce (*Picea rubens* Sarg.) trees in the area began to die in large numbers. The initial survey indicated that the affected trees were killed by the southern pine beetle (*Dendroctonus frontalis* Zimm.). This insect is not normally successful at colonizing these tree species because the trees produce large amounts of oleoresin that exclude the boring beetles. Subsequent investigations revealed that long-term acid deposition may have altered red spruce forest structure and function. There is some evidence that elevated acid deposition (particularly nitrogen) reduced tree water uptake potential, oleoresin production, and caused the trees to become more susceptible to insect colonization during the drought period. While the ecosystem was not in exceedance of the CAL, long-term nitrogen deposition pre-disposed the forest to other ecological stress. In combination, insects, drought, and nitrogen ultimately combined to cause the observed forest mortality. If any one of these factors were not present, the trees would likely not have died. This paper presents a conceptual framework of the ecosystem consequences of these interactions as well as limited plot level data to support this concept. Future assessments of the use of CAL studies need to account for multiple stress impacts to better understand ecosystem response.

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1. Introduction

Air borne nitrogen (N) and sulfur (S) from industry and automobile exhaust has been falling across Europe and the eastern United States (US) for over 60 years in the form of acid rain. Heavily polluted areas can receive over $890 \text{ eq N ha}^{-1} \text{ yr}^{-1}$ (Holland et al., 2005) alone. The environmental impacts of air pollutants have been

studied since N and S were first suspected to cause forest damage and decline across Europe and the Northeastern US in the mid 1980s. Chronic inputs of N deposition can cause leaching of base cations from the soil (McLaughlin et al., 1998), tree mortality (McNulty et al., 2005) increase aluminum toxicity to roots (Shortle and Smith, 1988), decrease fine root biomass (Nadehoffer, 2000), reduce tree cold tolerance (Sheppard, 1994), and increase freezing injury in spruce needles (Schaberg et al., 2002).

Traditionally, an ecosystem is considered to be at risk for health impairment when its critical N and S load exceeds a pre-determined level. Deposition in excess of the critical acid load (CAL) is

* Corresponding author. Tel.: +1 919 515 9489; fax: +1 919 513 2978.

E-mail address: steve_mcnulty@ncsu.edu (S.G. McNulty).

termed the *acid exceedance*, and the larger the acid exceedance, the greater the risk of ecosystem damage. This definition of CAL applies to a single, long-term acid exposure, and does not include episodic disturbance impacts.

Various methods have been designed to test the CAL of an ecosystem. One of the most popular methods for determining an ecosystem's CAL is the use of a simple mass balance equation (Posch et al., 2001; Gregor et al., 2004; McNulty et al., 2007). The simple model uses static soil, climate, vegetation, and pollutant deposition data to estimate an ecosystem's CAL, with the assumption being that current and future environmental conditions will have the same patterns of stress as historic conditions.

However, a static CAL level may not accurately assess ecosystem risk to damage when an ecosystem is subjected to multiple, episodic environmental stresses. If multiple stress impacts (i.e., extreme drought, heat waves, fire, insects and disease) are included in CAL assessments, CALs may need to be lowered in many areas to maintain long-term ecosystem health. Climate change could both directly (via changes in drought and heat wave cycles), and indirectly (via changes in insect, disease, and wildfire patterns and severity) impact ecosystem health, and the way that CALs are assessed for an ecosystem. We will conceptually examine how climate change might directly and indirectly alter the ecosystem parameters that are used in a simple mass balance equation for determining critical acid loading to better understand ecosystem response to integrated environmental stress.

2. 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 (Katz and Brown, 1992; Houghton et al., 2001). Both inter-decadal shifts in climate and inter-annual climate variability can influence the CAL of an ecosystem.

2.1. Drought

Water is one of the principle determinants of ecosystem type. Average annual precipitation in temperate forests ranges from 500 to 2500 mm per year. Deserts, scrublands, and woodlands receive between 0 and 1250 mm of precipitation per year (Whittaker, 1970).

Short-term (i.e., less than two years) drought can cause reduced ecosystem productivity (Hanson and Weltzin, 2000), reduced leaf longevity in deciduous species (Jonasson et al., 1996), and reduced leaf area (Gholz et al., 1991). These factors reduce plant biological demand for nitrogen and other nutrients. Under extreme drought, reduced soil moisture can cause reduced nitrogen mineralization and nitrification that then result in reduced ammonium and nitrate availability. These conditions will cause little short-term impact on CAL if both nitrogen demand and supply are reduced. However, nitrogen and sulfur deposition will continue to accumulate in the ecosystem, and a nitrate pulse could occur following a drought if nitrogen mineralization and nitrification rates respond more quickly to available water than do increases in plant demand for nitrogen (Gundersen, 1998). Therefore, the ecosystem may experience short-term acidification immediately following the drought with associated changes in forest structure and function.

Long-term (i.e., greater than two years) drought can cause additional ecosystem disruptions, and therefore have the potential to significantly lower ecosystem CAL levels. Long-term droughts have all of the characteristics of short-term drought (described above) plus the potential for tree mortality due to water stress

(Kloppel et al., 2003), increased insect outbreak potential (Mattson and Haack, 1987), and increased fire risk (Flannigan et al., 2000). As with the short-term drought, long-term drought may reduce biological nitrogen demand and supply. Additionally, the potential for tree mortality could lead to a significant decrease in biological nitrogen demand. If tree mortality is severe, a large nitrate pulse could occur following the drought, similar to the nitrogen pulse observed following forest harvesting (Vitousek and Matson, 1985). The CAL may be significantly reduced for several years after drought-induced forest mortality, because new growth cannot fully utilize existing water, light, and nutrients. The long-term drought affect will vary across sites and species as some tree species or ecosystems are more adaptive and less restricted in their growth by drought and warmer temperatures (Orwig and Abrams, 1997).

2.2. Climate change shifts on water availability

Both short- and long-term droughts are transient weather events. However, climate change can cause a permanent shift in the amount and timing of precipitation for a region. Changes in tree species, nutrient cycling, and water flow are also likely with climatic shifts. Reductions in precipitation would cause a shift toward more open, drought tolerant woodlands (Hansen et al., 2001). As tree density decreases, nitrogen demand and uptake by vegetation decreases. Therefore, the CAL for an ecosystem receiving less precipitation would likely decrease. Conversely, the CAL could increase if climate change causes an increase in precipitation, along with a shift toward more dense forests with higher nitrogen demands. Long-term precipitation change-induced forest species shifts can also change the nitrogen cycle. Mesic tree species have a tendency to be more nitrogen demanding (Watmough and Dillon, 2004), and thus potentially increase the CAL.

2.3. Increased air temperature

During the next century, substantial changes are expected in air 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 between 2 and 6 °C above 1990 levels by 2100 (IPCC, 2007). While all general circulation models predict that the earth will warm over the next century, the degree and distribution of the warming is uncertain (IPCC, 2007).

Many biological processes are linked to air temperature. Litter decomposition, soil nitrogen mineralization, and soil nitrification will increase with increasing air temperature (Stevenson, 1986; Anderson, 1991). These changes in soil nutrient cycles as well as plant biodiversity and density may be affected if rapid tree species shifts or migrations are achieved due to warmer temperature (Iverson and Prasad, 1998; Iverson et al., 2008). For example, if a conifer forest becomes a deciduous forest, the likely affect on the soil will be changes in nutrient cycling due to a more rapid uptake of nutrients (e.g., nitrogen) by more nitrogen demanding species. If this occurs and species migration change ecosystems properties, then it is plausible that area CALs will increase because of the increase in nitrogen uptake. In contrast, increases in both nitrogen demand and supply can offset each other, and the CAL may not change. However, if tree nitrogen demand does not keep pace with nitrogen availability, then CALs could decrease with increasing air temperature. There are limits or knowledge gaps in understanding the affects and degree to which large scale species migration can occur (Clark, 1998).

2.4. Fire impacts on critical acid loads

From 1994 to 2004, an average of 1.6 million hectares of forestland was burned by wildfire every year in the US alone (National Interagency Fire Center, 2005). Over 50 years of fire suppression have led to a significant accumulation of fire fuels across the US (van Wageningen, 1985). Climate change could impact the likelihood of wildfires due to warmer air temperatures (Fried et al., 2004), increased lightning strikes (Price and Rind, 1994) and changed atmospheric synoptic patterns (i.e., movement of the jet stream, Heilman, 1995). Increased fuel loads and global warming have resulted in an increase in area burned (Westerling et al., 2006), with over 3.2 million hectares burned in both 2004 and 2005 (National Interagency Fire Center, 2005). Both controlled burns and wildfires significantly impact forest structure and function, which in turn affect the CAL of the ecosystem.

Low impact wildfires can influence CAL levels in ways similar to a controlled burn, while high intensity wildfires can significantly alter ecosystem structure and function for many years (National Wildfire Coordinating Group, 2001) and can have both positive and negative impacts on ecosystem CAL levels.

Short-term (i.e., less than two years) negative impacts of wildfires include the loss of soil cation exchange capacity (CEC) and organic matter that reduce the ecosystem CAL (Arocena and Opio, 2003). Wildfires can burn hot enough to sterilize the soil and volatilize organic nitrogen (Harwood and Jackson, 1975; Boyer and Dell, 1980; Baird et al., 1999), which then greatly reduces total soil microbial biomass and soil processes such as nitrogen mineralization (Dunn et al., 1979). Under these conditions, ammonium deposition may be a significant source of nitrogen needed for plant regeneration while nitrate deposition may be rapidly leached through the soil, and thus increase the soil's CAL.

However, over the long-term (i.e., more than two years), even intense wildfires can significantly increase the CAL levels of an ecosystem. Other macronutrients (e.g., magnesium (Mg), calcium (Ca), potassium (K), phosphorus (P)) generally increase with fire (both controlled and wild) as biomass is consumed and the inorganic elements are returned to the soil (Johnson et al., 2005). An increase in macronutrients can stimulate plant growth (Grier et al., 1989), which increases plant demand for nitrogen and increases the long-term CAL level. For example, in Yellowstone National Park wildfires initially destroyed much of the forest in 1988 (National Interagency Fire Center, 2005). Several years were required to re-establish the ecosystems, but now species diversity and forest growth have been restored to pre-burn conditions (Turner et al., 2003). Therefore, it is possible that CAL levels are now higher across the park than before the wildfires.

2.5. Insects and disease

Functionally, insects and diseases can impact an ecosystem's CAL in similar ways. Both have the ability to either injure or kill the host tree. Reductions in tree growth can reduce both base cation and nitrogen uptake (Grier et al., 1989; Hogberg et al., 2006). Conversely, disturbances can result in detrital material serving as a fertilizer to the soil, and result in increased productivity and cation uptake by tree species in future years (Jenkins et al., 1999; Yorks et al., 2000).

Unlike widespread climate events such as drought or heat waves, insect and disease outbreaks can be selective of species or forest type (i.e., conifer vs. deciduous). Changes in species composition could eventually cause changes in forest nutrient balances (Mooney et al., 1999). Both disease and insect outbreaks can also lead to near total forest mortality. Under these conditions, major changes in nutrient dynamics can be expected. Reductions in cation

uptake, increases in forest floor temperatures and associated increases in nitrogen mineralization and nitrification rates could occur (Vitousek et al., 1989; McNulty et al., 2005). As the plants decay, increases in soil organic matter could also increase water holding capacity leading to increased productivity and cation uptake (Edwards and Ross-Todd, 1979). Therefore, insect and disease events can impact forest soil's CALs levels very differently than either climate or fire related disturbances.

2.6. Variability in disturbance impacts on an ecosystem's critical acid loads

Not all disturbance impacts have a universally negative or positive affect on forest soil's CALs. For example, wildfires negatively impact soil's CALs by generally reducing soil organic matter content and soil CEC. However, wildfires can also positively impact soil's CALs by increasing soil pH and macronutrient content. Also, the stress impacts are not universally negative or positive in all areas. Binkley et al. (1992) found that controlled burns increased the C:N ratio in coastal pine organic horizon ecosystems. However, Klopatek et al. (1990) found that controlled fire reduced the soil C:N ratio in pinyon-juniper ecosystems. Therefore, controlled burns may increase the CAL in one ecosystem while reducing it in another. This example illustrates the need to assessing the impact of disturbance impacts of soil's critical acid loading on an individual ecosystem basis. Generalities are useful only in understanding how CALs of most ecosystems respond to disturbance, not in predicting specific ecosystem impacts.

2.7. Combined impacts

Thus far, this paper has only examined how climate change, insects, disease and fires can impact individual ecosystem CAL parameters (e.g., soil pH, CEC and nitrogen mineralization, and tree nitrogen uptake). Now we will inferentially examine how combinations of changing ecosystem parameters impact an ecosystem's CAL. A single ecosystem may have a large change in its CAL depending on the type and severity of non-nitrogen ecosystem stresses. For example, the base CAL for forest soil, as calculated from a simple mass balance equation, could equal 270 eq N ha⁻¹ yr⁻¹ (Fig. 1a). However, drought can significantly reduce available soil water and plant growth. In turn, reductions in plant growth reduce nitrogen uptake, which then reduce the ecosystem's ability to use and store nitrogen. Therefore, under a drought, the same ecosystem may have its CAL reduced to 180 eq N ha⁻¹ yr⁻¹ (Fig. 1b).

Prolonged drought can also reduce the ability of trees to produce secondary compounds such as oleoresin (Lorio and Hodges, 1977). Without resin, insects have a much greater potential for successfully colonizing and causing tree mortality (Nebeker et al., 1993). In combination, a prolonged drought and subsequent insect attack could further reduce the CAL of the ecosystem to 140 eq N ha⁻¹ yr⁻¹ (Fig. 1c).

Increases in air temperature may have implications for forest health across the US as the climate becomes warmer and more variable. These conditions created by increases in temperature are important to predisposing plants to changes in growth and water stress (McNulty and Swank, 1995; Ferrio et al., 2003). As previously discussed, temperature can also significantly alter site and nutrient status reducing the CAL of an ecosystem. Therefore, the same ecosystem that experiences drought, insect, and temperature impacts may now only have a CAL of 90 eq N ha⁻¹ yr⁻¹ (Fig. 1d).

As demonstrated by this example, there is no single CAL level for any given ecosystem, even if nitrogen and sulfur deposition levels remain constant. Land managers and policy makers need to recognize that whole ecosystem management is necessary if we

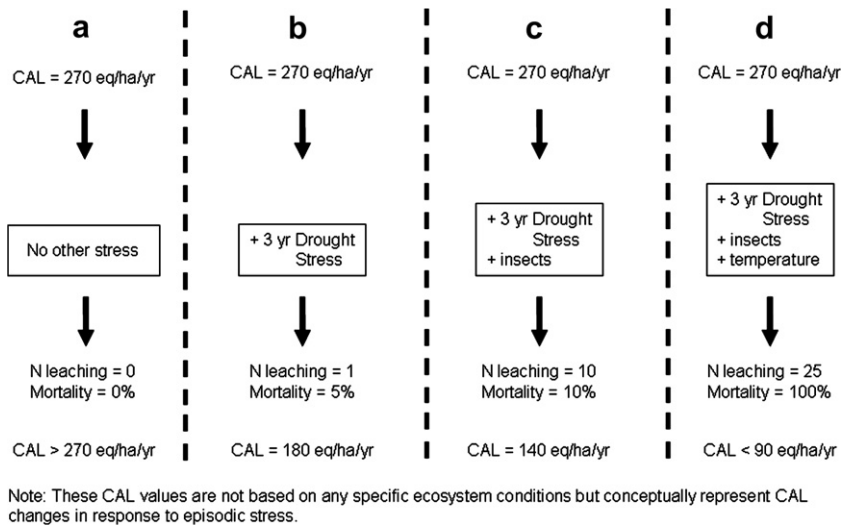


Fig. 1. Forest soil's critical acid loads (CALs) could change within the same ecosystem under episodic stress.

wish to avoid exceeding an ecosystem's ability to absorb acid. Although several national scale CAL assessments have been completed (Strickland et al., 1993; McNulty et al., 2007; Carou et al., 2008), great caution should be used in interpreting this information at any specific location.

3. Case study of variable critical acid load

3.1. General background

Since the 1960s, the southern pine beetle (*Dendroctonus frontalis* Zimm.) has been one of the most destructive insects across southern pine forests (Price et al., 1996) but these insects are normally confined to low elevation pine (*Pinus* sp.) forests. However, in 2001, high elevation red spruce (*Picea rubens*, Sarg.) stands on Mount Mitchell in western NC, North Carolina, USA began to die, and upon closer examination, we determined that the southern pine beetles were present and may have caused the observed forest mortality.

Beetle outbreaks are rare in these forests, given that red spruce produce large amounts of resin that should prevent successful beetle colonization and girdling of the phloem tissue, which is the primary cause of death. A national scale forest CAL assessment suggested that although the area received high levels of acid loading, these levels were not in exceedance of the soil's CAL (McNulty et al., 2007). So why did the model not predict that the area was in exceedance of the soil's CAL? Was the model incorrectly parameterized, or were other factors responsible for the observed forest mortality?

3.2. Case study measurements

We toured the affected area in 2001 and collected soil samples, tree cores, and foliage from areas with mostly living trees (i.e., over 95% of basal area living) and from areas of high (i.e., over 95% of basal area dead) red spruce mortality. Meteorological data was also retrieved from a nearby (less than 5 km distant) weather station.

During the period 1996–2000, average annual growing season precipitation and temperature was 538 mm and 14.2 °C, which was the driest and warmest five year period over the past 50 years. The disturbance history of the Mount Mitchell area is unknown. However, much of this area has experienced significant ecological and species

changes during the 20th century that has significantly influenced soil nutrient balances (Silver, 2003).

3.3. Case study findings

Prior to the mortality, red spruce basal area was significantly higher on the plots that had high rates of mortality during the drought (i.e., "dead plots") compared to plots with low post drought mortality (i.e., "live plots") and other surveys of red spruce basal area on Mount Mitchell (Bowers, 2005). The forest floor in the dead plots had significantly higher exchangeable potassium, magnesium, and calcium concentrations, percent base saturation, forest floor N concentration, and net potential N mineralization and nitrification rates than did the live plots. Cation exchange capacity and pH between the live and dead plots was not significantly different. This suggests that the plots with dead trees were more fertile which resulted in faster tree growth compared to the plots which had lower rates of mortality during the beetle outbreak, even though the climate conditions were likely identical.

Foliar N concentration and Mg:N ratios from live trees on live plots and residual live trees from the dead plots were significantly different. The highest foliar N concentration and lowest Mg:N ratio was measured in the residual live spruce foliage from the predominately dead plots. Measured foliar N concentrations were relatively high: 1.3% on the residual live trees on dead plots and 1.1% on the live trees on the live plots. In Ponderosa and Jeffrey pine forests, Jones et al. (2004) found that tree mortality and beetle activity were significantly higher on sites receiving high inputs of N due to changes in ecosystem functioning.

Basal area growth in live trees on the live plots showed little response to an earlier (1986–1990) drought and had higher wood $\Delta^{13}\text{C}$ when compared to the trees on the dead plots. Annual tree rings record the $\Delta^{13}\text{C}$, and provide a record of tree water stress (McNulty and Swank, 1995; Ferrio et al., 2003), with larger $\Delta^{13}\text{C}$ values indicating lower water stress.

3.4. Interactions among Agents in case study

Many studies have shown links between soil fertility and increases in biomass production (Jones et al., 2004; Magill et al., 2004; McNulty et al., 2005). However, coupling temperature increases, N deposition, and drought with the characteristics of the

highly fertile site (dead plots) may have created the negative environmental condition for the red spruce trees exposed to southern pine beetles. Increases in temperature may have increased red spruce evapotranspiration rates, triggering tree stress (Mitchell et al., 1990; Rosenberg et al., 1990). While chronic acidic deposition did not create an exceedance of the CAL, the rates of acidic deposition may have caused nutrient imbalances (Schulze, 1989; McNulty et al., 2005), increased freeze injury to foliage (Schaberg et al., 1997), and reduced red spruce cold tolerance (Sheppard, 1994; Schaberg et al., 2002). Drought conditions may have fostered changes within the red spruce trees that suppressed their defense response mechanism (i.e., oleoresin production) to both abiotic and biotic stressors. For example, resin production is reduced in pine species during hot, droughty periods (Hodges and Lorio, 1975; Hodges et al., 1979). Cook and Hain (1987) reported that shortleaf pine species susceptible to insect infestation had a lower resin flow rate than resistant trees. McDowell et al. (2007) found that resin production increased linearly with basal area increment and decreased linearly with stand basal area on equivalent sites. Although we did not measure the root biomass, the trees that were growing on the dead plots may have been adding more aboveground biomass than belowground resulting in higher stand basal area and lower resin production from trees in the dead plots when compared to trees in the live plots.

4. Conclusions

Our planet's climate is changing, and these changes are impacting forest health both directly through droughts and heat waves, and indirectly through increased fire, insect and disease occurrences. However, climate change is not happening in a vacuum. Acidic deposition is still an environmental problem for many forests. Researchers have developed models for assessing acidic deposition impacts to forest soils in an attempt to better maintain forest health. While these models may provide some indication of potential problem areas, they are often based on the premise that other environmental stresses fall within a historic range of occurrence and severity. Under climate change, this increasingly appears to be a false assumption. Forests appear much less able to tolerate elevated acid loading when subjected to multiple stresses. Future assessment of forest CALs and exceedances need to address the dynamic nature of multiple environmental stress if improvements in identifying areas of potentially impaired forest health are to be achieved.

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