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

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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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A B S T R A C T

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 eq N ha^{-1} 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

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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 termed 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 (Kloeppel 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).