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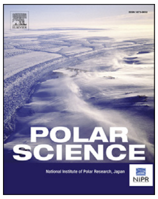

Evaluating the relationship between wildfire extent and nitrogen dry deposition in a boreal forest in interior Alaska

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ABSTRACT

Alaska wildfires may play an important role in nitrogen (N) dry deposition in Alaskan boreal forests. Here we used annual N dry deposition data measured by CASTNET at Denali National Park (DEN417) during 1999–2013, to evaluate the relationships between wildfire extent and N dry deposition in Alaska. We established six potential factors for multiple regression analysis, including burned area within 100 km of DEN417 (BA_{100km}) and in other distant parts of Alaska (BA_{AK}), the sum of indexes of North Atlantic Oscillation and Arctic Oscillation (OI), number of days with negative OI (OI_{day}), precipitation (PRCP), and number of days with PRCP ($PRCP_{day}$). Multiple regression analysis was conducted for both time scales, annual (using only annual values of factors) and six-month (using annual values of BA_{AK} and BA_{100km}, and fire and non-fire seasons' values of other four factors) time scales. Together, BA_{AK}, BA_{100km}, and OI_{day}, along with $PRCP_{day}$ in the case of the six-month scale, explained more than 92% of the interannual variation in N dry deposition. The influence of BA_{100km} on N dry deposition was ten-fold greater than from BA_{AK}; the qualitative contribution was almost zero, however, due to the small BA_{100km}. BA_{AK} was the leading explanatory factor, with a 15 ± 14% contribution. We further calculated N dry deposition during 1950–2013 using the obtained regression equation and long-term records for the factors. The N dry deposition calculated for 1950–2013 revealed that an increased occurrence of wildfires during the 2000s led to the maximum N dry deposition exhibited during this decade. As a result, the effect of BA_{AK} on N dry deposition remains sufficiently large, even when large possible uncertainties (>40%) in the measurement of N dry deposition are taken into account for the multiple regression analysis.

1. Introduction

Boreal forests cover 10% of the global terrestrial area and more than 50% of interior Alaska (Kasischke et al., 2010), where more rapid warming has been reported compared to lower latitudes (Collins et al., 2013). So far, several studies have been conducted to evaluate the responses from carbon, nutrient, and water exchanges in boreal forest ecosystems to climate changes (Chapin et al., 2006).

Nitrogen (N) availability is an important factor in the control of carbon and water cycling, as well as biodiversity, in boreal forests. The low temperature and anaerobic soil conditions associated with permafrost-impeded drainage constrain the decomposition rate, leading to the formation of thick layers of soil organic matter (Chapin et al., 2006). Consequently, the turnover rate for nutrients in boreal forests is generally slow (Valentine et al., 2006), and tree growth is in return restricted by N availability (Janssens et al., 2010). In this ecosystem, a change in N availability affects various biological functions, such as biological N_2 fixation and composition of the forest floor (Gundale et al., 2011).

Dry deposition is one of the major N-input pathways in boreal forests, along with wet deposition and biological N_2 fixation. Total N deposition (wet + dry) is rarely measured in interior Alaska, though estimates have put it at 30–100 mg N m^{-2} $year^{-1}$, of which 30% is dry deposition, as reported by the Clean Air Status and Trends Network (CASTNET, 2014; Jones et al., 2005). N_2 fixation in these boreal forests varies from 20 to 200 mg N m^{-2} $year^{-1}$, both between and within forest stands (Markham, 2009).

Wildfires may play an important role in N dry deposition in the boreal forests of interior Alaska. During summers in the 2000s,

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approximately 500 wildfires a year burned a decadal average of 7000 km^2 [AICC (Alaska Interagency Coordination Center), 2014]. In addition, due to global warming, the extent of wildfires across Alaska and Canada is predicted to increase by 3.5–5.5 times by the last decade of the 21st century, compared with the last decade of the 20th century (Balshi et al., 2009). It is also commonly observed that the concentrations of aerosol particles and precursor gasses over forests increase episodically, due to advection of wildfire smoke (Polissar et al., 1998). These particles and gasses from wildfires are transported within smoke, resulting in N supply to forests through dry and wet deposition. However, wildfire-associated N dry deposition in boreal forests, especially in Alaska, has not yet been investigated extensively. CASTNET has monitored N dry deposition at one location in interior Alaska since 1999, although these data have not been analyzed in detail for the effects of Alaska wildfires.

An examination of the effects of the multiple factors that could contribute to N dry deposition is required to improve the precision and accuracy of estimates of contributions from wildfires to N dry deposition. Major factors include long-range transport, rain and snow scavenging, and anthropogenic emissions of N compounds (Galloway et al., 2004), as well as local wildfire occurrence. Among these factors, long-range transport, rain and snow scavenging, and wildfires usually show greater interannual variation than does anthropogenic N emission, due to dependence on atmospheric flow patterns and weather conditions. Therefore, we hypothesize that long-range transport, rain scavenging, and local wildfires have the greatest effect on interannual variations in N dry deposition. In addition, the amount of N dry deposition at a particular location may be related to its distance from each wildfire. Our second hypothesis supposes that closer wildfires result in greater deposition than more distant wildfires.

We used the North Atlantic Oscillation (NAO) index and the Arctic Oscillation (AO) index for a variable representing long-range transport, and daily precipitation for representing rain and snow scavenging. NAO and AO describe a redistribution of atmospheric mass between the Arctic and the Subtropics: the positive phase is associated with lower sea-level pressure over the Arctic and higher sea-level pressure over the North Atlantic compared to normal conditions, and the negative phase is associated with opposite pressure conditions (Di Pierro et al., 2013). NAO and AO exert strong control over long-range transport from Europe and Eurasia through the Arctic Ocean (Di Pierro et al., 2013). This is one of the major pathways for air pollutants to interior Alaska, becoming active particularly during the cold season (Atkinson et al., 2013). During the warm season, NAO and AO decreases, and transport is weakened. Rain and snow scavenging have negative effects on dry deposition by removing aerosol and gaseous pollutant from the air.

In this study, we focus on clarifying the contributions of wildfires to N dry deposition in a boreal forest in interior Alaska (DEN417), by applying a multiple regression analysis to CASTNET dry deposition data and climate data. In addition, we calculated N dry deposition for 1950–2013 by assuming that the obtained relationship between N dry deposition and factors is applicable on a long-term basis.

2. Materials and methods

2.1. General scheme of data analysis

2.1.1. Multiple regression analysis

We evaluated the contribution from each factor to annual N dry deposition in a boreal forest in interior Alaska for 1999–2013, using multiple regression analysis with stepwise model selection. The factors evaluated included burned area within 100 km of DEN417 (BA_{100km}) and in other distant parts of Alaska (BA_{AK}), sum of daily indexes of North Atlantic Oscillation and Arctic Oscillation (OI), number of negative OI days (OI_{day}), precipitation amount (PRCP), and number of rainy and snowy days ($PRCP_{day}$). Time scales for N dry deposition, BA_{AK}, and BA_{100km} were annual. Time scales for the other four factors were originally by day, and summed both annually and six–monthly. In the case of the six–month scale, daily values for factors in the year were summed for the fire season (April–September) and non-fire season (January–March and October–December), separately.

We then conducted a multiple regression analysis with model selection using the MuMIn package (MuMIn, 2016) of the CRAN R software 3.2.2 (R Core Team, 2015). In MuMIn's multiple regression analysis, the regression equation was solved as a generalized linear model, with the model minimizing Akaike's Information Criterion with a correction for finite sample sizes, known as AICc, selected as the best from all possible models (MuMIn, 2016). We conducted MuMIn's multiple regression analysis for both time scales, annually (using only annual values of factors) and six-monthly (using annual values for BA_{AK} and BA_{100km}, and fire and non-fire season values for other factors). We first obtained a correlation matrix, in order to examine the independence of each factor from the others.

The following regression equation enabled evaluation of the contributions from each factor to N dry deposition:

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \cdots \beta_i X_i \qquad 1$$

,where Y is an annual N dry deposition response variable, X_i is an exploratory variable of factor i, α is a background deposition constant, and β_i is the partial regression coefficient of factor i. We calculated $\beta_i X_i / Y$ of each factor for every year, and determined fifteen-year averages and standard deviations for $\beta_i X_i / Y$, as contributions from each factor to N dry deposition. We further evaluated the strength of the influence from each factor on N dry deposition, using a normalized partial regression coefficient (β_i^*). Following a statistically common method, β_i^* is defined as:

$$\beta_i^* = \beta_i \frac{S_{X_i}}{S_y} \qquad 2$$

,where S_{xi} is the standard deviation of each factor, and S_{yi} is the standard deviation of N dry deposition.

In addition to multiple regression analysis, the determination coefficient, adjusted for data number ($n = 15$) and factor number ($e = 1$–6) in the model (known as adjusted $R2$), was compared to effect sizes, to evaluate whether frequency of data and number of factors for the model were sufficient for the analysis. The effect size in statistical analysis is the measure of strength of the phenomenon under investigation (Orwin, 1983), and is calculated as R^2 with desired data frequency, factor number, Type I error probability (usually 0.05), and Type II error probability (usually 0.2) using the pwr package (Champely, 2015) in CRAN R software 3.2.2. An adjusted R^2 larger than the effect size for the model suggests the effect of model is sufficiently large for the desired data frequency and factor number.

2.1.2. Calculation of long-term N dry deposition for 1950–2013

We calculated N dry deposition in the Alaska boreal forest for 1950–2013 by applying the regression equations obtained from the multiple regression analysis, together with long-term records for factors. This calculated N dry deposition for the past sixty-four years enabled discussion of the effects from the increased wildfire occurrence in the 2000s on N dry deposition.

According to Galloway et al. (2004), global total N deposition has increased exponentially, from 31.6 Tg N $year^{-1}$ in 1860 to 103 Tg N