



# Northern Hemisphere forests at temperate and boreal latitudes are substantial pollen contributors to atmospheric bioaerosols



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## ABSTRACT

Forest pollen is a heavy contributor to atmospheric bioaerosols during spring months. This is important because bioaerosols make up 25% of the atmospheric aerosols shaping cloud formation, precipitation and ultimately climate. To test this premise, we drew from available literature, a meta-analysis of 25 forest pollen reports and a comparative analysis of *Zea mays* versus *Pinus taeda* pollen. Using available literature, we showed forest pollen grains are not too large or too few in the atmosphere and that some types are prone to bursting into subpollen particles (SPP). High forest pollen concentrations were consistent in the meta-analysis of 25 forest pollen reports from 1937 to 2014 at Northern Hemisphere latitudes ranging from 33°N to 64°N. In eight reports, pollen concentrations exceeded 10<sup>4</sup> grains m<sup>-3</sup> for birch (*Betula* spp.), spruce (*Picea* spp.), pines (*Pinus* spp.) and alder (*Alnus* spp.). Southern Hemisphere forests had low forest pollen concentrations. *Pinus taeda*, as a woody perennial species, produced more pollen by three orders of magnitude when compared to *Zea mays* which serves as the current source of generalized global pollen emissions for general circulation models. *Pinus taeda* alone accounted for 3.3 Tg y<sup>-1</sup> of the world's current estimate of global pollen emissions although its land area occupies only 0.2% of the world's forests. Forest pollen, whether intact and burst, is shown here to have the capacity for altitudinal ascent, atmospheric residency and long-distance transport. Thus forest pollen is concluded to be a substantial contributor to atmospheric bioaerosols for higher latitudes during spring in the Northern Hemisphere.

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## 1. Introduction

Atmospheric biology is experiencing renewed interest (Womack et al., 2010; Després et al., 2012; Fröhlich-Nowoisky

et al., 2016) but its interface with forests and forest pollen is still a neglected research area. Forest pollen<sup>1</sup> emissions at temperate and boreal latitudes are hypothesized here to be substantial enough

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<sup>1</sup> During its flight, pollen is not a container for male gametes. Gametes form after deposition and after the pollen tube emerges, or germinates. Strictly speaking, a pollen grain ( $d \geq 5\text{--}200\text{ }\mu\text{m}$ ) is a male gametophyte inside a spore wall. This mobile, multicellular phase is the haploid part of the diplohaplontic life cycle of seed plants.

**Table 1**  
Scaling extremes needed for studying pollen at the forest-atmosphere interface.

10 <sup>4</sup> m	thunderstorm (10 km altitudinal expanse)
10 <sup>−1</sup> m	hailstone, large (10 cm diameter)
10 <sup>−3</sup> m	raindrop, small (2 mm) to large (6 mm)
10 <sup>−5</sup> m	fungal spores (8–186 μm diameter)
10 <sup>−5</sup> m	pine pollen grain (30–70 μm diameter)
10 <sup>−6</sup> m	cloud condensation nucleus (≥1 μm)
10 <sup>−10</sup> m	water molecule 3 × 10 <sup>−10</sup>

to influence atmospheric aerosol composition and cloud formation on regional scales. Exploring this hypothesis first requires biology to recognize the extreme scaling inherent to this area of research inquiry within the atmospheric sciences (Table 1). Global emissions for biological particles, inclusive of pollen, is defined as primary biological aerosol particles (PBAPs). Annual biogenic emissions are estimated as high as 1000 Tg y<sup>−1</sup> (Table 2) yet this is moderate when compared to inert components of atmospheric aerosols such as dust, salt, volcanic ash and black carbon (Table 2). PBAPs, composing about 25% or less of atmospheric aerosols (Jaenicke et al., 2007), remain similar yearlong so that only their composition shifts seasonally, as shown during peak forest pollen release in eastern Siberia (Matthias-Maser et al., 2000). Quantifying the seasonal forest pollen contribution to atmosphere aerosol studies required a literature review, a meta-analysis of forest pollen concentration reports at higher latitudes and a per-plant comparison between forest and annual plant species.

Forest pollen’s contribution to atmospheric aerosols has long been thought to be negligible but this is quickly changing. This change is presented as a set of tested hypotheses (Table 3), showing that surprising experimental outcomes support forests as a substantial contributor of pollen to atmospheric studies. Some types of forest pollen are prone to bursting into subpollen particles (SPP). Pine and spruce pollen are sampled in high-altitude updrafts up to 2–5 km above the earth’s surface (Table 3; Rempe, 1937;

**Table 2**  
Atmospheric aerosol composition expressed as global emission averages (adapted from Boucher et al. (2013) Chapter 7 Table 7.1B page 596).

Atmospheric aerosol composition	Global emissions, Tg year <sup>−1</sup>
Sea spray	1400–6800
Mineral dust	1000–4000
Primary Biological Atmospheric Particles (PBAPs); (Jacobson and Streets, 2009; Hoose et al., 2010; Jaenicke et al., 2007)	1000

**Table 3**  
Hypotheses tested to date about atmospheric concentrations of forest pollen.

Null hypotheses for forest pollen contribution to atmospheric aerosols	Accept/reject	Cited literature
(1) H <sub>0</sub> : Pollen grains are too large and too few	Reject	Bursting sub-pollen particles (SPP) in lab simulations ascend to higher altitudes (Augustin et al., 2013)
(2) H <sub>0</sub> : Pollen grains have low-altitude ascendancy	Reject	Hailstones, aircraft sampled over USA (Mandrioli et al., 1973; Mandrioli et al., 1984)
(3) H <sub>0</sub> : Pollen grains have short residency times	Reject	Jet stream transport of substantial pollen-laden air parcels from Quebec to Arctic Nunavut in four days (Campbell et al., 1999)
(4) H <sub>0</sub> : Pollen grains have short transport distances	Reject	Pollen deposition above Arctic treeline in Greenland (i.e. Campbell et al., 1999; Rousseau et al., 2006)

Sassen, 2008; Mandrioli et al., 1984) and pine pollen is inside large hailstones (Mandrioli et al., 1973). Numerous studies show pollen-laden air parcels are transported thousands of kilometers above the Arctic treeline (Table 3). These are a few examples drawn from a literature rich with experimental, historical and anecdotal support. While it seems likely that only 10–40% of forest pollen is dispersed by vertical transport (Gregory, 1978; Rempe, 1937), this seasonal contribution may still large enough to influence the role of atmospheric aerosols on regional climate.

Global pollen emissions for atmospheric studies so far are generalized from *Zea mays* pollen (Jacobson and Streets, 2009). These estimates are exceedingly small with global emissions estimate only reaching 84.3 Tg y<sup>−1</sup> (Jacobson and Streets, 2009) and this was halved to 47 Tg y<sup>−1</sup> when simulating effect of primary biological aerosol particles (PBAPs) on general circulation models (GCM) (Hoose et al., 2010). Annual crops provided the only pollen estimate for both of these atmospheric aerosol studies. Using these values, pollen and other PBAPs are shown to have no effect on general circulation models (GCM) of earth systems used for global climate forecasting (Hoose et al., 2010). More recent findings support our premise: re-analysis on regional scales is timely and necessary.

*Subpollen particles (SPP)*. Birch and other types of forest pollen grains burst into sub-pollen particles (SPP) (Pummer et al., 2012; Augustin et al., 2013; Steiner et al., 2015). SPP float to higher altitudes, rich in water-soluble ice-nucleating and ice-binding molecules (Dreischmeier et al., 2016). These molecules have a capacity to modify cloud ice and ultimately precipitation. As such, bursting pollen fragments (SPP) are seen to have a multiplier effect. This effect has yet to be tested in atmospheric studies; so far they have been tested only under laboratory conditions. The SPP source is birch and some other types of forest pollen which thus influence cloud formation processes related to ice-nucleating and ice-binding (Diehl et al., 2002). A well-documented case study is *Juniperus* spp and some other species from the Cupressaceae family which bursts, spreading allergenic proteins in the human respiratory tract (Tomlinson, 1994; Rogers and Levettin, 1998). Forest pollen grains, in light of bursting, cannot be assumed to be too large and too few in atmospheric bioaerosols (Table 2).

*Annual plant species produce less pollen than perennial species*. Consider that tree pollen accounted for 75% of the lower atmosphere count while annual plants accounted for only 21% in Turkey (Türe and Böcük, 2009). Woody perennial plants add crown height and crown volume annually which in turn translates into greater pollen production. Another factor favoring forest trees is that its pollen will be released ever-increasing heights, roughly from five to 50 m from the earth’s surface, where wind speeds are higher. Relying on *Zea mays* pollen generalizations for global pollen production seems overly conservative.

*GCM models use annual averages on a global scale*. A different scale may be needed for biogenic emissions, pollen included. GCM models were not designed to test vertical atmospheric profiles although this is where aerosols affect cloud formation processes (i.e. Boucher et al., 2013). There is also a shift to regional climate models (RCM) which are now preferred for forecasting because they align more closely with daily human activity (Boucher et al., 2013). A re-analysis on regional scale should also simulate seasonal phenology and doing so would include seasonal forest pollen release. How atmospheric bioaerosols shape cloud formation are hypothesized here to have regional and seasonal influences attributed to shifting PBAP composition.

How (or if) pollen from temperate and boreal forests contributes to atmosphere aerosols and cloud formation on regional scales has thus matured into an important question. Supporting our premise required further steps: (1) a meta-analysis approach to quantify forest pollen concentrations and (2) a per-plant comparison of pollen production between annual and forest species.

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