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Meteorological factors associated with abundance of airborne fungal spores over natural vegetation

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HIGHLIGHTS

- Fungal spore abundance peaked during the wet season over natural vegetation.
- Air temperature and relative humidity strongly correspond with spore density.
- Meteorology versus vegetation drives spore density across spatio-temporal scales.

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ABSTRACT

The abundance of airborne fungal spores in agricultural and urban settings increases with greater air temperature, relative humidity, or precipitation. The same meteorological factors that affect temporal patterns in spore abundance in managed environments also vary spatially across natural habitats in association with differences in vegetation structure. Here we investigated how temporal and spatial variation in aerial spore abundance is affected by abiotic (weather) and biotic (vegetation) factors as a foundation for predicting how fungi may respond to changes in weather and land-use patterns. We measured the phenology of airborne fungal spores across a mosaic of naturally occurring vegetation types at different time scales to describe (1) how spore abundance changes over time, (2) which local meteorological variables are good predictors for airborne spore density, and (3) whether spore abundance differs across vegetation types. Using an air volumetric vacuum sampler, we collected spore samples at 3-h intervals over a 120-h period in a mixed-evergreen forest and coastal prairie to measure diurnal, nocturnal, and total airborne spore abundance across vegetation types. Spore samples were also collected at weekly and monthly intervals in mixed-evergreen forest, redwood forest, and maritime chaparral vegetation types from 12 field sites across two years. We found greater airborne spore densities during the wetter winter months compared to the drier summer months. Mean total spore abundance in the mixed-evergreen forest was twice than in the coastal prairie, but there were no significant differences in total airborne spore abundance among mixed-evergreen forest, redwood forest, and maritime chaparral vegetation types. Weekly and monthly peaks in airborne spore abundance corresponded with rain events and peaks in soil moisture. Overall, temporal patterns in meteorological factors were much more important in determining airborne fungal spore abundance than the vegetation type. This suggests that overall patterns of fungal spore dynamics may be predictable across heterogeneous landscapes based on local weather patterns.

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1. Introduction

Fungi are important as pathogens, mutualists, and decomposers of plants and animals in ecosystems worldwide (Brown and Hovmøller, 2002; Daszak et al., 2000; Leake, 1994; Bardgett and van der Putten, 2014). Fungi disperse to new hosts and substrates by producing and releasing spores - small structures (2–20 μm) that serve for fungal reproduction and survival (Moore-Landecker, 2011). Once spores are produced and released they travel through the air (Elbert et al., 2007; Glikson et al., 1995), water, or soil (Fitt et al., 1989), or are carried by animals (Lilleskov and Bruns, 2005).

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Although some fungi can spread over short distances through the growth of thread-like hyphae (Agerer, 2001), spore release into the air is the most common mode of dispersal (Gregory, 1967; Egan et al., 2014). Most airborne spores come from fungi growing on living or dead plants (Burgess, 2002), and high abundances of airborne spores of plant pathogens such as *Alternaria* spp. or *Aspergillus* spp. can increase the risk of crop diseases (Langenberg et al., 1977; Bock et al., 2004) as well as respiratory illness in humans (Pringle, 2013; D'Amato et al., 2015). Moreover, airborne fungal spores are primary biological aerosol particles (PBAP) found in the atmosphere, along with bacteria, pollen, viruses, and organismal fragments; PBAPs can influence climate through their optical properties and act as cloud and ice nuclei (Després et al., 2012).

Previous studies from agriculture and urban environments point to the importance of meteorological conditions in driving airborne spore density (Burch and Levetin, 2002; Hock et al., 1995; Manstretta and Rossi, 2015). Airborne spore abundance generally increases when there are marked increases in air temperature (Langenberg et al., 1977), relative humidity (Webster et al., 1989), or precipitation (Gregory, 1967; Velez-Pereira et al., 2016). Warm air temperatures are positively correlated with high airborne spore densities of *Alternaria* spp., *Cladosporium* spp., and *Epicoccum* spp. (Aira et al., 2013; Corden et al., 2003; Grinn-Gofron and Strzelczak, 2012; Troutt and Levetin, 2001). An increase in relative humidity can trigger spore release which increases the abundance of spores in the air (Leyronas and Nicot, 2013; Gabey et al., 2010). Rain also triggers spore release (Aylor and Sutton, 1992), and the moist soil and leaf conditions that persist after a rain event contribute to an increase in airborne fungal spore densities (Ganthaler and Mayr, 2015). Fungal spores also contribute to the organic carbon content and aerosol mass balance of the air (Després et al., 2012). Bioaerosol size and concentrations are found to change across locations and seasons (Bauer et al., 2008; Yamamoto et al., 2012; Zhu et al., 2015).

In order to understand the epidemiology of fungal diseases of crops, agricultural scientists have long measured the timing of spore release, or spore phenology (McCartney, 1994), and the relationship between spore phenology and environmental conditions. Disease forecasting models are often based on measurement of spore release during a host plant's growing season (Huber and Gillespie, 1992; Small et al., 2015) and the relationship between spore abundance and critical points in plant development (Fouré and Ganry, 2008; Xu and Berrie, 2014). A sudden rise in air temperature and relative humidity can cue fungal sporulation on plant parts, leaf litter, or the soil surface (Levetin and Dorsey, 2006; Fernández-González et al., 2009). Airborne spores can then land on plant surfaces through either dry or wet deposition (Fuentes and Gillespie, 1992; Grove and Biggs, 2006). Subsequent spore germination and plant disease development is then enhanced by extended leaf wetness (Bradley et al., 2003; Guyader et al., 2013; Huber and Gillespie, 1992). Coordinated measurements of airborne spore density, host development and reproduction, and the timing, duration, and magnitude of local meteorological conditions (e.g., precipitation, leaf wetness) are critical foundations for plant disease forecasting models (Wu et al., 2002).

Most research on fungal spore phenology has focused on agricultural or human pathogens. From these studies we know that meteorological factors (Burch and Levetin, 2002) and vegetation type (Skjøth et al., 2016) drive the timing of spore release and the quantity of airborne spore loads (Stepalska and Wolek, 2009); we would expect similar patterns to hold in less heavily managed land-use types or natural systems (e.g., forests, shrub-lands) where fewer spore phenology studies have been conducted (Bowers et al., 2013; Alexander, 2010; Gilbert and Reynolds, 2005). Understanding how spore phenology responds to abiotic (weather) and biotic (vegetation) factors in natural systems can help us predict how fungi will respond to changes in climate (D'Amato et al., 2015; Velez-Pereira et al., 2016) and land-use patterns (Bowers et al., 2013) and the implications of such changes for disease incidence.

In the Mediterranean climate of California, we anticipated that spore loads measured over natural vegetation would be the highest during the moist winter growing season compared to the dry summer season, and that at shorter time scales, airborne spore abundance would increase along with air temperature and relative humidity and following rainfall events. Airborne spore abundance should be higher in forested habitats compared to open-vegetation-like prairie or chaparral because structurally complex forests typically have more available plant biomass as substrate for fungal growth. This study was conducted to measure the phenology of airborne fungal spores across a mosaic of natural vegetation types on the central coast of California at different time scales and asked 1) does spore abundance change predictably over time? 2) which meteorological variables are reliable predictors for airborne spore loads, and 3) how does spore abundance differ across vegetation types?

2. Materials and methods

2.1. Field sites

This research was conducted on the University of California, Santa Cruz (UCSC) Natural Reserve and in adjacent Wilder Ranch State Park in Santa Cruz County, California, USA (Fig. 1, Appendix A.1).

The region experiences a Mediterranean type climate with mild, wet winters and hot, dry summers with a total average annual precipitation of approximately 745 mm (Appendix B.1). Although maritime fog inundates the coast of California between July and September (Johnstone and Dawson, 2009), the majority of precipitation (approximately 745 mm) falls as rain in the winter and spring months from October to April (Appendix B.1, Gilbert et al., 2010). Four major terrestrial vegetation types form a natural mosaic across the landscape: redwood forest, mixed-evergreen forest, coastal prairie, and maritime chaparral (Sawyer and Keeler-Wolf, 2009; Haff et al., 2008).

We selected field sites using topographic maps and vegetation data that were obtained from reserve and state park managers. In order to find suitable sites for spore sampling, we visualized our

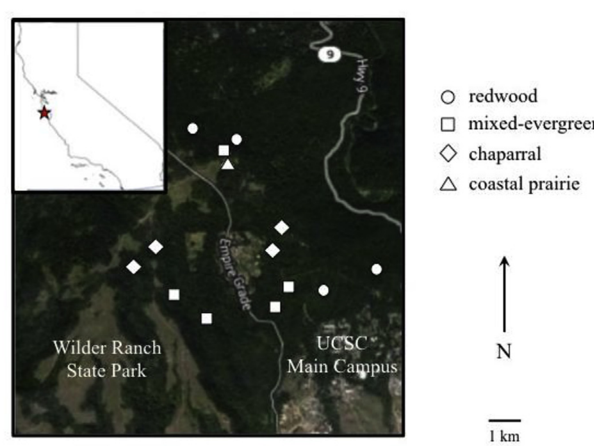

Fig. 1. Field sites on the central coast of California, USA (inset); locations where volumetric air samples data and meteorological data were collected in 2013 and 2014.

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