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Abundance of *Ganoderma* sp. in Europe and SW Asia: modelling the pathogen infection levels in local trees using the proxy of airborne fungal spore concentrations

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What do these dates mean?

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Highlights

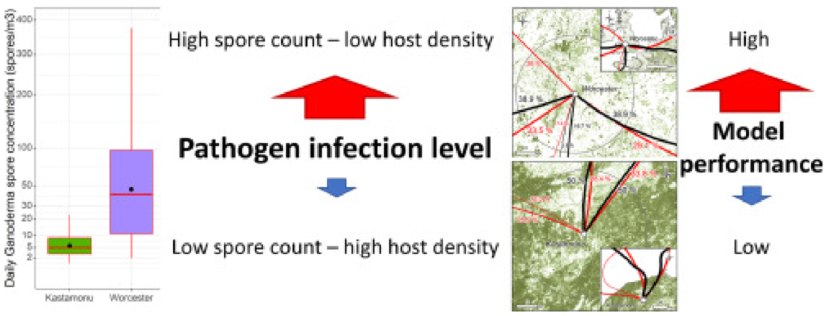
- The locations of potential pathogen host areas were identified for each study site.
- A new Pathogen Infection Level Index is developed to assess relative pathogen abundance.
- Local thermal variables were most important to predict airborne *Ganoderma* spore concentrations.
- Whilst local sources of *Ganoderma* spores are a major source, long-distance transport is also a factor at some sites.
- UK woodlands were more severely infected with *Ganoderma* species than the other sites investigated.

Abstract

Ganoderma comprises a common bracket fungal genus that causes basal stem rot in deciduous and coniferous trees and palms, thus having a large economic impact on forestry production. We estimated pathogen abundance using long-term, daily spore concentration data collected in five biogeographic regions in Europe and SW Asia. We hypothesized that pathogen abundance in the air depends on the density of potential hosts (trees) in the surrounding area, and that its spores originate locally. We tested this hypothesis by (1) calculating tree cover density, (2) assessing the impact of local meteorological variables on spore concentration, (3) computing back trajectories, (4) developing random forest models predicting daily spore concentration. The area covered by trees was calculated based on Tree Density Datasets within a 30 km radius from sampling sites. Variations in daily and seasonal spore concentrations were cross-examined between sites using a selection of statistical tools including HYSPLIT and random forest models.

Our results showed that spore concentrations were higher in Northern and Central Europe than in South Europe and SW Asia. High and unusually high spore concentrations (> 90th and > 98th percentile, respectively) were partially associated with long distance transported spores: at least 33% of *Ganoderma* spores recorded in Madeira during days with high concentrations originated from the Iberian Peninsula located >900 km away. Random forest models developed on local meteorological data performed better in sites where the contribution of long distance transported spores was lower. We found that high concentrations were recorded in sites with low host density (Leicester, Worcester), and low concentrations in Kastamonu with high host density. This suggests that south European and SW Asian forests may be less severely affected by *Ganoderma*. This study highlights the effectiveness of monitoring airborne *Ganoderma* spore concentrations as a tool for assessing local *Ganoderma* pathogen infection levels.

Graphical abstract



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Introduction

Ganoderma species are wood-decaying basidiomycete fungi with a cosmopolitan distribution, and they comprise common pathogens on deciduous and coniferous trees, as well as palms with stems without secondary growth. The fungi reproduce via airborne spores and grow in the non-living tissues. They usually attack dead, weakened or damaged trees, however, recent surveys of basidiomycete endophytes revealed that wood-decaying fungi, including *Ganoderma* species, can be found in wood of living trees too (Song et al., 2017). Pathogenicity studies revealed that the investigated *Ganoderma* species are capable of infecting healthy sapwood following trunk wounding, however, they are not usually pathogens in young, actively-growing trees that only possess sapwood (Loyd et al., 2018).

Ganoderma sp. enzymes allow them to break down wood components such as lignin and cellulose (Schwarze et al., 2000). Delignification and defibration caused by undisturbed rotting extend throughout the interior of the trunk making the tree susceptible to wind damage (Blanchette et al., 1985; Dill and Kraepelin, 1986). Based on the type of decay caused by *Ganoderma* species, they are classified as white rot fungi (the infected wood becomes wet, spongy or stringy and the colour changes to white or yellow). Several approaches are needed to control white rot infection. Most have been trialed in oil palm plantations due to serious economic losses (Flood et al., 2005; Paterson, 2007). Some control methods can be extrapolated to the deciduous and coniferous commercial forests, e.g. infection sources should be reduced at the time of clearing old stands by removing infected debris and *Ganoderma* sp. fruiting bodies (Panchal and Bridge, 2005), and all infected plant material should be treated with a specific type of biofungicide (Soepena et al., 2000). An important problem related to white rot control, however, is the lack of sufficient information on variation in *Ganoderma* species associated with disease and their mode of reproduction.

Ganoderma is taxonomically considered as the most difficult genus among all those in the Polyporales order and is in a state of taxonomical chaos (Ryvarden, 1985, Ryvarden, 1991). Taxonomists have described 326 legitimate *Ganoderma* species and lower taxa (Robert et al., 2013). Among these only 7 species are accepted in the European polypore monographs: *G. adspersum*, *G. applanatum*, *G. carnosum*, *G. cupreolaccatum* (syn. *G. pfeifferi*), *G. lucidum*, *G. resinaceum* and *G. valesiacum* (e.g. Pegler and Young, 1973; Ryvarden and Gilbertson, 1993; Sokół, 2000; Wojewoda, 2003). *G. adspersum* occurs on *Alnus* sp., *Fraxinus* sp., *Carpinus* sp., *Morus* sp., *Quercus* sp., *Juglans* sp., *Ulmus* sp. and very rarely on conifers; *G. applanatum* occurs mainly on deciduous trees (*Alnus* sp., *Betula* sp., *Carpinus* sp., *Fagus* sp., *Quercus* sp., *Salix* sp., *Populus* sp.), less frequently on coniferous (*Abies* sp., *Picea* sp., very rare on *Pinus* sp.); *G. carnosum* infects mainly conifers (*Abies* sp., *Taxus* sp.) but rarely occurs on deciduous tree species; *G. cupreolaccatum* prefers to live on *Fagus* sp. and rarely on a variety of other deciduous trees (*Aesculus* sp., *Acer* sp., *Fraxinus* sp., *Prunus* sp., *Quercus* sp.); *G. lucidum* grows on *Quercus* sp., *Carpinus* sp., *Salix* sp., *Corylus* sp., *Acer* sp. and very rarely on conifers; *G. resinaceum* infects only deciduous trees (*Quercus* sp., *Salix* sp.); *G. valesiacum* is a Central European species occurring predominantly in montane to subalpine regions, in the natural stands of *Larix* sp. (Ryvarden and Gilbertson, 1993; Sokół, 2000; Szczepkowski and Piętka, 2003; Papp and Szabó, 2013; Lindequist et al., 2015).

Ganoderma spores can be an important component of atmospheric bioaerosols. A single *G. applanatum* basidiocarp can produce 30 billion spores per day, over a period of six months (Meredith, 1973; Levetin, 1990). Airborne fungal spores are able to travel long distances via air mass transport (Edman et al., 2004; Sesartic and Dallafior, 2011), so studying *Ganoderma* spore concentrations in the air may be relevant from the forestry and the economic perspective on a large landscape scale. In England, the Forest Commission highlighted *Ganoderma* genus as an important pathogen (McKay, 2011). Similar negative impacts on forestry can be expected in other regions, but this has so far not been quantified.

A limited number of aerobiological studies have focused on characterizing daily and seasonal patterns of *Ganoderma* spore occurrence, and relationships between spore concentration and meteorological parameters, often in the context of the allergenic properties of *Ganoderma* spp. (Tarlo et al., 1979; Levetin, 1991; Craig and Levetin, 2000; Hasnain et al., 2004; Kadowaki et al., 2010; Grinn-Gofroń and Strzelczak, 2011; Kasprzyk et al., 2011; Grinn-Gofroń et al., 2015; Jędryczka et al., 2015; Sadyś et al., 2016).

Until now, the only research on the distribution of *Ganoderma* spores among different landscapes was conducted in the UK (Sadyś et al., 2014). Back-trajectories from that study showed export of these spores from forests to agricultural and urban areas, and the results suggested the main sources of this pathogen were located within a 200 km range from the trap site (Worcester, UK). No evidence of long-distance spore transport from the main continent was found.

In the present study, we hypothesize that *Ganoderma* spores originate from local sources, and therefore that spore concentrations can be predicted using local meteorological data. Moreover, if local fungal sources are crucial for spore concentration, the relative pathogen infection level can be determined by combining airborne spore concentrations and the area covered by potential tree hosts. To test these hypotheses we used aerobiological records from seven sites, representing five biogeographical regions and four climate types, and aimed to (1) estimate the host (tree) density at different distances from each trapping site; (2) determine the spore season parameters; (3) assess the relationships between primary meteorological variables and airborne spore concentrations (4) calculate the backward trajectories indicating pathways of possible *Ganoderma* spores transport to sites; and, (5) compute machine learning models for *Ganoderma* spore concentration in the air.

Section snippets

Spore identification, sampling and a comparison between receptor sites

Ganoderma spp. (hereafter *Ganoderma*) spores have either an egg or ovoid shape and they are approx. 4.5–8 × 8–13 μm in size (Pegler and Young, 1973; Fig. 1). *Ganoderma* can be distinguished from other bracket fungi because it possesses a double-walled basidiospore. The external spore wall is transparent and smooth, while the internal wall varies from dark brown to golden in colour. The wall layers are connected by pillars, which under the microscope may resemble dots. Another distinctive feature …

Spore seasons across Europe and SW Asia

The shortest spore season was recorded in Kastamonu (109 days) and Vinnytsia (125 days) whereas the longest (282 days) was in Funchal/Madeira. The *Ganoderma* spore season started earliest in southern Europe and SW Asia, i.e., in Funchal/Madeira (February), then in Adana (March). The *Ganoderma* spore season started in May in Worcester, Leicester and Vinnytsia, and started latest in in Szczecin and Kastamonu, in June. The difference in spore season start dates between Funchal/Madeira and Kastamonu …

Discussion

Airborne *Ganoderma* spore concentrations were recorded in five different biogeographical regions representing four climate types in Europe and SW Asia. The highest airborne concentrations in Europe were found to the North (Latitudes > 45°N) whilst there were low levels in the South of Europe and the studied part of Asia. This may result from the higher humidity levels in the northern part of the study area; previous studies have shown a positive relationship between high humidity and *Ganoderma* …

Conclusions

This is the first comprehensive study of airborne *Ganoderma* spores and thus *Ganoderma* pathogen abundance in Europe and SW Asia. We found significant differences in *Ganoderma* spore concentrations and season timing between four different climates and five biogeographical regions, and showed that the concentrations increased with increasing latitudes (up to 55°N). Airborne *Ganoderma* concentrations were positively associated with thermal variables at all sites apart from Madeira Island, although …

CRediT authorship contribution statement

AGG: Conceptualization, methodology, data curation, writing original draft, reviewing and approving final draft; PB, JN: methodology, writing original draft, reviewing and approving final draft; BB: Conceptualization, writing original draft, reviewing and approving final draft; CAS, VR, TC: provision of data, data curation, reviewing and approving final draft; IC, MS, CHP: provision of data, data curation, writing original draft, reviewing and approving final draft; CTH: reviewing and approving ...

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. ...

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