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Fungal spores are transported long distances in smoke from biomass fires

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Abstract

Viable fungal spores are present in smoke from distant biomass fires. This finding has potentially important implications for prescribed burning, agricultural management and public health. While attempting to find fungal spores in dust blown from China to Texas, one of us (S.A.M.) discovered that smoke from Yucatan contains viable bacteria and fungal spores, including the genera *Alternaria, Cladosporium, Fusariella* and *Curvularia*. There was a high correlation ($r^2 = 0.78$) of spores and coarse carbon particles collected on microscope slides during 13 days of the 2002 smoke season. To eliminate possible contamination by local spores, an air sampler was flown from a kite at a Texas Gulf Coast beach during and after the 2003 smoke season on days when the NOAA back trajectory showed air arriving from Yucatan. Fifty-two spores and 19 coarse black carbon particles ($>2.5\,\mu m$) were collected during a 30-min kite flight on the smoke day and 12 spores and four carbons on the day without smoke. We have found spores in smoke from an Arizona forest fire and in Asian smoke at Mauna Loa Observatory, Hawaii. We have tested these findings by burning dried grass, leaves, twigs and flood detritus. The smoke from all test fires contained many spores.

Keywords: Prescribed fires; Agricultural fires; Public health; Carbon; Dust

1. Introduction

We have found that convection caused by biomass fires can launch fungal spores and bacteria skyward, where they may travel thousands of kilometers. While the long-distance transport of fungal spores on currents of air is well established (Meier and Lindbergh, 1935; Brown and Hovmoller, 2002), we are unaware of a prior publication that describes fire-induced convection as a mechanism for initiating such long-distance transport. Karnal bunt, a smut infection of wheat caused by *Tilletia indica*, can spread by convection to surrounding fields when diseased wheat is burned (Roux and O'Brien, 2001). This disease has spread around the world from its origin in India, and the findings reported here suggest that fire-induced convection might spread pathogenic spores much greater distances than surrounding fields.

Sugarcane rust caused by the fungus *Puccinia melanocephala*, appeared in the Dominican Republic in July 1978. Purdy et al. (1985) suggest this outbreak followed transoceanic transport of spores from West Africa. Because sugarcane is burned at harvest, we suggest that convection caused by fire could have launched spores into the air stream that delivered inoculum to the Caribbean. Burning of diseased plants is so widespread, and often mandated, that there are many similar scenarios for the launching of pathogenic microbes by fire-induced convection.

There is an abundant literature on long-distance transport of fungi that are pathogenic to plants and that cause allergic reactions when inhaled by people (Kendrick, 2000; Griffin et al., 2001; Brown and Hovmoller, 2002). Microbes are unique among particulate

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matter, for, unlike nonviable particles, microbes can rapidly multiply. Thus, the transport of a small number of pathogenic spores can result in the eventual infection of entire fields. This phenomenon is well known and can sometimes be forecast. For example, the North American Plant Disease Forecast Center at North Carolina State University publishes on the Internet forward trajectories of *Pseudoperonospora cubensis*, which causes Downy mildew in squash, cucumbers, pumpkins, and muskmelons, and *Peronospora tabacina* Adam, which infects tobacco (Main et al., 2001). Similar forecasts might be relevant to smoke events.

2. Fungal spores and Central American smoke

Fungal spores and bacteria are associated with dust that originates in North Africa and reaches the Caribbean. Griffin et al. (2001) discuss bacteria and spores associated with Sahara dust transported across the Atlantic. Shinn et al. (2000) describes how the soil fungus *Aspergillus* in Sahara dust infects Caribbean coral reefs. During a study in April 2002 to determine if viable microbes are transported with dust transported from Asia to Texas, one of us (S.A.M.) serendipitously discovered many viable fungal spores and bacteria associated with smoke arriving at Geronimo Creek Observatory in South-Central Texas (29.6N, 97.9W) from large fires in Yucatan, Mexico.

2.1. Central American smoke at Central Texas, 2002

During the April 2002 smoke event, the Navy Aerosol Analysis and Prediction System (NAAPS) aerosol forecast model (US Naval Research Observatory, www.nrlmry.navy.mil/aerosol/) showed that the smoke originating in Yucatan traveled some 1450 km and reached Geronimo Creek Observatory in 2–3 days. The smoke reduced visibility, increased the optical depth measured by Sun photometers, created a pronounced solar aureole, and caused sharp increases in the number of 0.5 μm particles.

On 13 days during this event, a microscope slide was placed on a 4-m meteorological tower in an open field to collect coarse carbon particles (diameter >2.5 μm) and spores. At local noon, two nutrient media films (3 M Petrifilms (TM)), one formulated for bacteria (Petrifilm Aerobic) and one for fungi (Petrifilm Yeast and Mold), were hydrated with distilled water, exposed for 15 min on the tower, and incubated 3 days at ambient temperature.

Many colonies of fungi and bacteria grew on the films exposed during the smoke episode. The microscope slides permitted the numerical relationship of the spores and coarse carbon particles in the smoke to be quantified. Four scans across the width of each slide were made, and all spores and coarse carbon particles were counted. Fungal spores included representatives from 22 genera, including *Alternaria, Cladosporium*, *Fusariella, Nigrospora*, and *Curvularia*. As shown in Fig. 1, the correlation of all coarse carbon particles and spores deposited on slides during the smoke episode was very high ($r^2 = 0.78$). However, the correlation of some genera with carbon particles was very low (e.g., $r^2 =$ 0.00 and 0.05). These were likely local in origin.

2.2. Central American smoke at Texas Gulf Coast, 2003

Smoke from Yucatan again reached Texas during May 2003. A passive air sampler designed by S.A.M. was flown from a kite over a beach at North Padre Island, Texas (27.4N, 97.3W), on days when smoke from Yucatan was present and not present to eliminate interference from spores originating in Texas. Fig. 2 summarizes the kite experiments.

On 3 May 2003 (Fig. 2a, c and d), NOAA back trajectories showed that air at the Texas Gulf Coast had passed over Yucatan 48 h earlier. Terra MODIS and SeaWiFS imagery showed that smoke from fires in Yucatan covered the Western Gulf of Mexico. During the kite flight, a nearby monitoring station (CAMS 341) operated by the Texas Commission on Environmental Quality measured 16.1 μg/m^3 of PM 2.5 particles in air arriving from over open water at a mean direction of 134°. A 30-min flight captured 52 fungal spores and 19 coarse carbon particles (Fig. 2e).

On 5 August 2003, the NOAA back trajectory again showed air coming from Yucatan. Terra MODIS imagery showed no major fires in Yucatan and the study site. During the kite flight, CAMS 341 measured 5.5 μg/m^3 of PM 2.5 particles in wind arriving from over open water at a mean direction of 161°. A 30-min flight captured 12 fungal spores and four coarse carbon particles (Fig. 2f).

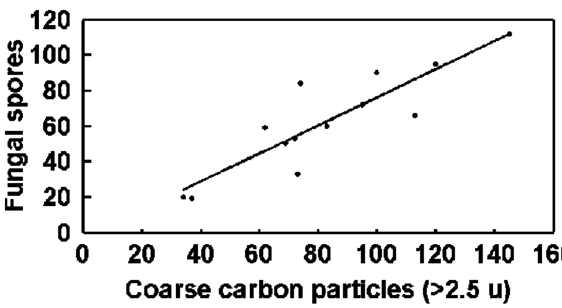

Fig. 1. *Xy* scattergraph ($r^2 = 0.78$) of fungal spores and coarse carbon particles deposited by sedimentation on exposed microscope slides at Geronimo Creek Observatory in South Central Texas on all 13 days samples were collected from 25 April–10 May 2002 during a major Central American smoke event.

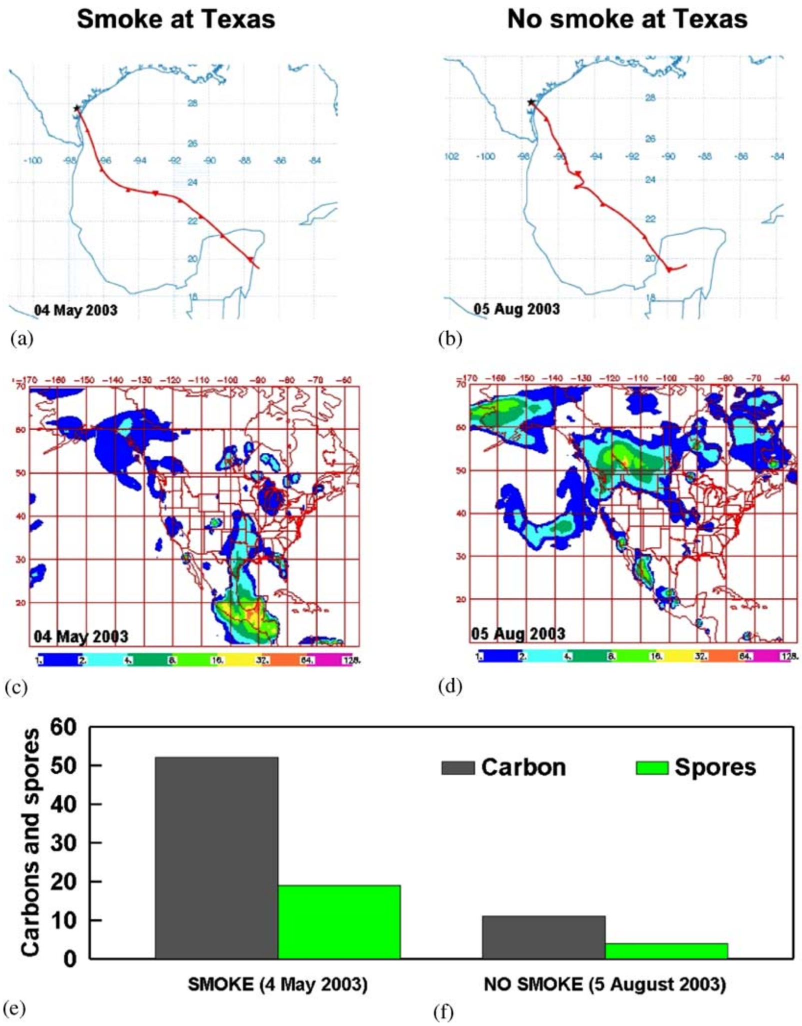

Fig. 2. On days when the NOAA back trajectory (a,b) indicated air arrived at North Padre Island, Texas, from Yucatan 48 h earlier (4 May and 5 August 2003), an air sampler was flown from a kite at a Gulf Coast beach when smoke from Yucatan was present (c) and not present (d). During 30-min flights, the sampler collected 52 spores and 19 coarse carbons on the smoke day (e), and only 12 spores and four carbons on the nonsmoke day (f).

Spores collected by the kite sampler include many of those collected during the 2002 Yucatan smoke event, including the genera *Alternaria, Cladosporium*, *Fusariella* and *Curvularia*. The kite study provides compelling evidence that spores were present in smoke from Yucatan arriving at the Texas Gulf Coast.

3. Fungal spores in other smoke events

We collected fungal spores in smoke from a forest fire in Arizona (18 June 2003) and in smoke from Canada and Louisiana at College Station, Texas (10 August 2003). We collected *Alternaria* and other spores and carbon particles at Mauna Loa Observatory (MLO), Hawaii (elevation 3400 m), during a rare Asian smoke event (6 July 2003). The smoke formed distinct layers and was associated with high concentrations of ozone (>70 ppb), which were highly correlated ($r^2 = 0.98$) with the 5 μm particle count.

4. Experimental validation of fungal spores in smoke

A simple experiment was designed to determine if fungal spores and bacteria are present in smoke from burning grass. Four Petrifilms (two bacteria and two mold) were clipped to a horizontal pole and exposed to smoke from burning grass for 5 min. A second set of four Petrifilms was exposed to background air for 5 min.

After 3 days of incubation at ambient temperature, the films exposed to smoke had a total of >115 mold and >90 bacteria colony forming units (CFUs). Those exposed to background air had only 10 mold and eight bacterial CFUs.

Various kinds of biomass were placed on a steel plate in an open field and burned. Smoke from each fire was sampled for 1 min using three Petrifilms (mold only). The temperature of the films, which was monitored with noncontact IR thermometry, ranged from 34°C to 49°C. Between fires, the background air was sampled for 1 min using three Petrifilms. A wood walkway prevented contamination by local spores. After 3 days of incubation at ambient temperature, nutrient films exposed to smoke from all the biomass samples exhibited significantly more CFUs than those exposed to ambient air between burns. The ratios of total CFUs in smoke to CFUs in background air were 9:3 (dry grass), 19:0 (dry leaves), 48:4 (twigs) and 87:5 (flood detritus).

Our observations and photographs of test fires under a plant canopy suggest that agitation of leaves caused by turbulent convection (Pisaric, 2002) may dislodge spores, which are then carried upward with the warm plume. Nearer the ground, turbulent air rushing in to feed the flames may also carry spores into the smoke plume.

5. Conclusions

The common assumption that plant pathogens are killed by burning is contradicted by the spread of Karnal bunt to surrounding fields when wheat infected with *T. indica* is burned (Roux and O'Brien, 2001). Our findings of many fungal spores in smoke from all test fires, and from large fires in Yucatan more than 1500 km distant, suggest that plant pathogens might be spread considerably farther than surrounding fields. Some fungal spores we have found in smoke (e.g., *Alternaria*) cause allergic reactions and trigger asthma attack (Kendrick, 2000). Heretofore, such reactions have been attributed solely to smoke inhalation, and we propose that fungal spores may also play a role. We propose to test this hypothesis by comparing emergency department visits for asthma and allergy-related respiratory incidents with spore counts by the Aeroallergen Monitoring Network of the American Academy of Allergy, Asthma and Immunology (Anon, 2001), which reveal examples of high mold counts during smoke events. This study will also examine incidence of asthma attack in the weeks after major smoke events, for the progeny of spores transported with smoke might be an even greater problem.

Prescribed burns of diseased crops, brush, timber, slash and rubbish may disperse large numbers of pathogenic fungi. Major fires, which can produce smoke plumes 3 km or more high, could be much more effective in launching spores into the troposphere than surface wind storms. Small burns of diseased plants and cooking and heating with diseased firewood might disperse pathogenic spores on a smaller scale.

A beneficial role for spores carried skyward with forest fire smoke could be reinoculation of fire-sterilized soil with mycorrhizal fungi and the dispersal of such symbiotic fungi to new locations. We plan to test this hypothesis. We also plan to study the variety and number of spores and bacteria in smoke from various kinds of fires. The abundance of spores relative to coarse carbon particles, 3:1 for Yucatan smoke in Texas and 1:1 for Asian smoke at MLO, could have a slight influence on radiative transfer models, for spores are regularly shaped and often translucent, while coarse carbon is opaque, black and irregularly shaped.

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Tom Gill informed us that Central American smoke was present when fungal spores were first found in smoke. Mark Hartwig suggested the design hypothesis that dispersal in smoke of mycorrhizal fungal spores might be beneficial. John Barnes facilitated sampling at Mauna Loa Observatory. Gabriel Solis and Ryan Peschel assisted with test fires. Gerald Holmes informed us about the spread of Karnal bunt by burning. We thank those responsible for NOAA back trajectories, GSFC MODIS imagery and the NRL NAAPS model. We also thank Eugene Shinn for helpful discussions and the editor and two anonymous reviewers for suggestions that greatly improved the manuscript.

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