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Adv. Topics in Biometeorology & Micrometeorology
May 1st, 2021

Gaussian Plume Modeling of Pollen Dispersal at Laguna Ek'Naab

Abstract

This project implements a Gaussian Plume Dispersion Model for pollen fluxes, as determined by the sediment record of a tropical lake near the late-classic Mayan period archaeological site Witzna in Petén, Guatemala (Wahl et al. 2019). The purpose of the model is to corroborate the vegetation reconstruction created from the core through the use of micrometeorological dispersal modeling. This site was chosen for its archeological interest, as paleoecological analysis of the site has provided new interpretations of Mayan history in Petén. By modeling the pollen dispersion implicit in the vegetation reconstruction, this project investigates the distance at which one can confidently assume the land use history conclusions made in Wahl et al. are applicable. While theoretically useful, the model is not sufficiently well parametrized to yield meaningful results.

Introduction

Studies of pollen dispersal and footprints have always been of interest for paleoecologists. This is because palynological records used to indicate land use history, vegetation, or climatic change are derived from sediment cores which only preserve what is found within a limited distance of the core. As compared to microfossils, trace elements, and charcoal the spatial extent of this relationship for pollen is particularly unclear. Unlike most environmental signals, pollen can be transported by wind currents up to several thousand kilometers (Moraes et al. 2018, O'Connell et al. 2007, Millar et al. 2020). Although this is unlikely to comprise a major part of the pollen signals seen at Laguna Ek'Naab, it does generally distort the conclusions made at sites which receive a significant abundance of pollen through long-distance transport. I largely exclude this possibility for the sake of model simplicity, and because the primary plant types noted for long distance pollen transport are not present in the sediment record. Additionally, the location of Witzna 200km from the eastern coast of an isthmus with Easterly prevailing winds would preclude transport from more than 200km distance, barring a measurable cross ocean flux. Furthermore, although wind direction, speed, and other environmental variables can vary widely on a short timescale at any site, the pollen record's resolution is more indicative of wind speed averaged over a one to ten year period, and can therefore be reasonably represented by mean wind in the model.

Pollen dispersal is also a topic of interest for allergists and medical professionals. Many studies have utilized dispersal models to forecast days with a high chance of provoking pollen allergies (Emberlin 1994; Frenz et al. 1995; Schueler et al. 2006; D'Amato et al. 2007; Efstathiou et al. 2011; Zhang et al. 2014; Lara et al. 2019; Kim et al. 2020). These studies generally use modern pollen traps combined with land cover data to establish pollen dispersal paths, as the combination of these measurements allow for the correlation of pollen abundance with land cover, yielding a predictive model. However, in-situ measurements of land cover do not exist on the timescales of lacustrine sediment records and we can never know the exact representativeness of surrounding vegetation revealed by pollen trapped in sediment records Yet, dispersal models for paleoenvironmental time scales could improve certainty of site representativeness by making evident the land use history assumptions required to produce a given pollen record, and allowing their likelihood to be considered on the basis of more records than pollen alone. Accordingly this experiment makes no definitive claim about the possible footprint from which the sediment record at Witzna collects, but instead attempts to demonstrate the plausibility of a changing canopy distribution in producing a vegetation record similar to the one recorded.

Scientific Basis

Previous work has applied both Eurlerian and Langrangian dispersal schemes to pollen dispersal. Recently, Lagrangian Stochastic models have performed better than Eulerian schemes, and it appears that Gaussian dispersion may underestimate pollen deposition arriving from greater distances (Theuerkauf et al. 2013). Assumptions of horizontally homogeneous meteorology and stable stratification may also result in models that fail to capture long-distance transport (Helbig et al. 2004). However, for educational purposes, I still chose to pursue a perhaps less accurate but easier to implement Gaussian model. Despite their limitations, prior work has shown that if better parameterized, gaussian plume dispersion does in some cases produce reasonable calculations of pollen footprints (Loos et al. 2003). Other factors which contribute to pollen transport distance are plant adaptations such as partial and reversible pollen desiccation, which has been implicated in drought tolerance, presumably by making pollen more resilient under hostile environmental conditions (Pacini and Dolferus 2019). Highly sensitive pollen release mechanisms that favor positive dispersal conditions have also been documented (Laursen et al. 2007, Siljamo et al. 2012).

Two of the most commonly used pollen deposition models (Prentice and Sugita) rely on Sutton's equation for dispersion $Q(x) = Q(0)exp(-4v_g x^{n/2}/nu\sqrt{\pi}C_z)$, where Q(0) is the particle source strength and Q(x) is the number of particles still airborne at a measured distance x from the source, V_g is the velocity of deposition of particles (cm/sec), u is wind speed (cm/sec), C_z is a vertical diffusion coef, and n is a dimensionless turbulence parameter. While both rely on Sutton's equation, Prentice assumes pollen deposited in the lake falls directly from the atmosphere with no mixing and redeposition while Sugita assumes almost complete mixing (Jackson and Lyford 1999). The model used in this project more closely resembles the Prentice model, since stable stratification is assumed and atmospheric mixing is not parameterized. Although deposition velocity is a consideration in the equation above, I model the non-humidified case wherein a falling particle does not gain mass as it falls, and, with significant uncertainty, I understand this to be the aspect of the plume which requires v_g as a parameter so have therefore excluded it. The actual equation modeled is taken from Paul Connolly at the University of Manchester, and is given by C = $\frac{Q}{2\pi u * \delta_y \delta_z * \frac{e^{crosswind^2}}{2\delta_y^2} * \frac{e^{-Z-H^2}}{2\delta_z^2} + \frac{-e^{-Z-H^2}}{2\delta_z^2}}$ where

C describes the concentration of pollen at a point distance (x, y) from an origin. The need for x and y comes from the calculation of the crosswind, and the deviation of dispersal due to atmospheric stability sigma. More details of the calculation including calculations of vertical and horizontal standard deviations and crosswind are found in the model script.

Site Description

This project is concerned with a record taken from a tropical lake situated near a late-Mayan period archeological site in Petén, Guatemala. The presence of Poaceae pollen types in the record, in particular like *Zea Mays* indicate human cultivated species in the immediate vicinity of the lake. Conveniently, *Z. mays* (common maize, or corn) does not grow spontaneously in the wild without human cultivation, and therefore acts as a proxy for human presence in the area. Wahl et al. 2019 conclude a timeline for the occupation of the site from the absence of *Z. mays* and a charcoal layer indicating probable sacking by a rival city-state. The assumed catchment of the lake is 8.75km^2, and the prevailing winds are Easterly. The exact geographic coordinates and not publicly available due to concerns over theft of artefacts.

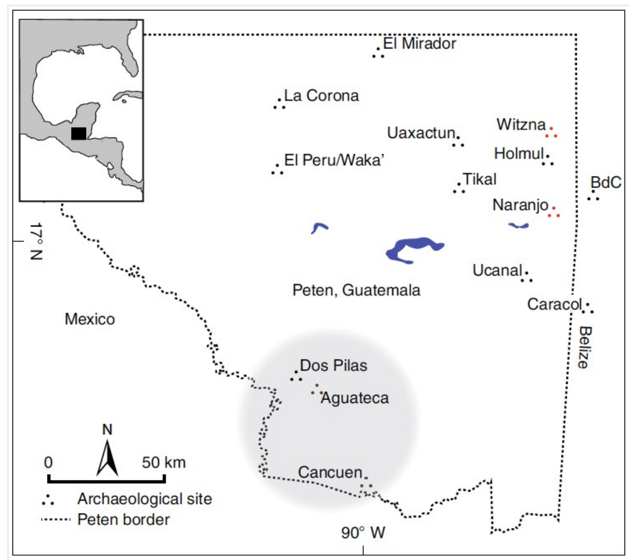
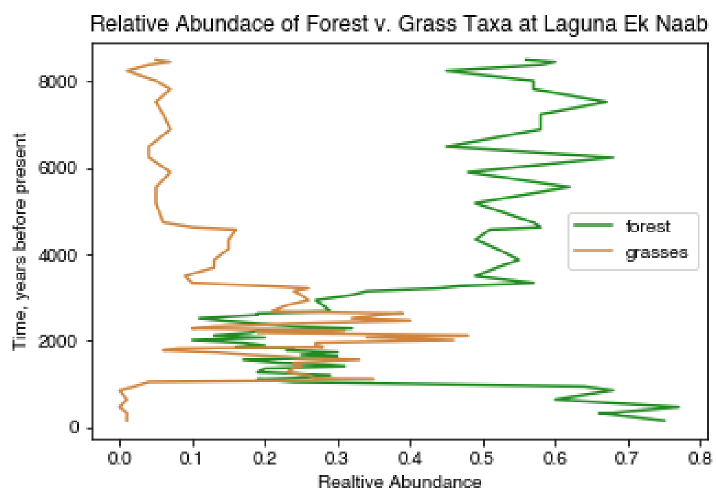


Figure 1. Relative location of Witzna in North-East Petén (above).

Figure 2. Relative abundance of taxa throughout core (below).



For archeological and cultural reasons, it would be interesting to discern the radius of the abandoned area, and if some former inhabitants may have occupied nearby sites after the burning of the city. Unfortunately sediment records of this kind rarely if ever can provide annual or even decadal resolution. For this reason, the outstanding archeological question of discerning between complete abandonment versus gradual emigration from the site is not possible based on the pollen record alone. However, through the use of footprint models it would be possible to determine a radius around the site which corresponds to the given record, and to indicate the radius within which humans were not active, helping archeologists be more certain about the extent of the site's abandonment.

Methods

Type	Common Name	Classification	Group	Overall Abundance
Urticales	Incl. mulberry, elm, nettle, cannabis, hops	Order	Forest	27.17%
Celtis	Hackberry	Genus	Forest	0.34%
Ficus	Fig	Genus	Forest	0.11%
Melastomataceae /Combretaceae	Incl. tropical flowering plants/mangrove	Family	Forest	12.26%
Asteraceae	Incl. aster/daisies	Family	Grass	3.96%
Ambrosia	Ragweed	Genus	Grass	1.92%
Poaceae (large)	Incl. grasses	Family	Grass	0.29%
Poaceae (small)	Incl. grasses	Family	Grass	10.17%

Table 1. Description of pollen data used in study

The pollen dataset used includes nine pollen types, each classified as either a forest or grass taxa according to Wahl et al. 2019 (Table 1.). Pollen records of increased grass taxa are considered indicative of forest clearance, habitation, and agriculture. Many unlisted genera account for a small amount of the total pollen, causing the total of the abundance column in Table 2. to be less than 100%. Consistent with the tropical rainforest setting, Urticales is the most abundant pollen group found in the record.

The model is implemented for three scenarios, where each corresponds to a probable stage of land use. These include (A, present-1500yBP) an uninhabited and relatively homogeneous forest site, (B, 1500-2000yB) an inhabited site with a sharp change in relative abundance of forest and grass taxa, and (C, 2000-8500yBP) a once again uninhabited forest site. The chosen time frames were derived based on the inversion of relative abundances in Figure 2. For each scenario, the number of individuals of each species is set to be 100 times its average relative abundance in that time period. Each individual is randomly assigned an (x, y) position on the $10km^2$ grid seen in Figure 3. Plants simulated as growing within the lake centered at (5500, 5500) with radius 0.5km are removed. Every individual of the same species is assigned the same plume distribution relative to its (x, y) location on the grid, and species differ only through their different initial values of pollen size and flux. Deposition velocity and variable fluxes within a species are not parameterized. This ignores both the fact that more mature plants of a given species may produce different amounts of pollen, and the importance of v_g. Finally, the emission fluxes from each individual are overlaid within each scenario, producing a net map of the pollen fluxes over the landscape as seen in Figure 4. Pollen deposited over the lake is again grouped between forest and grass taxa, and reported in Table 2.

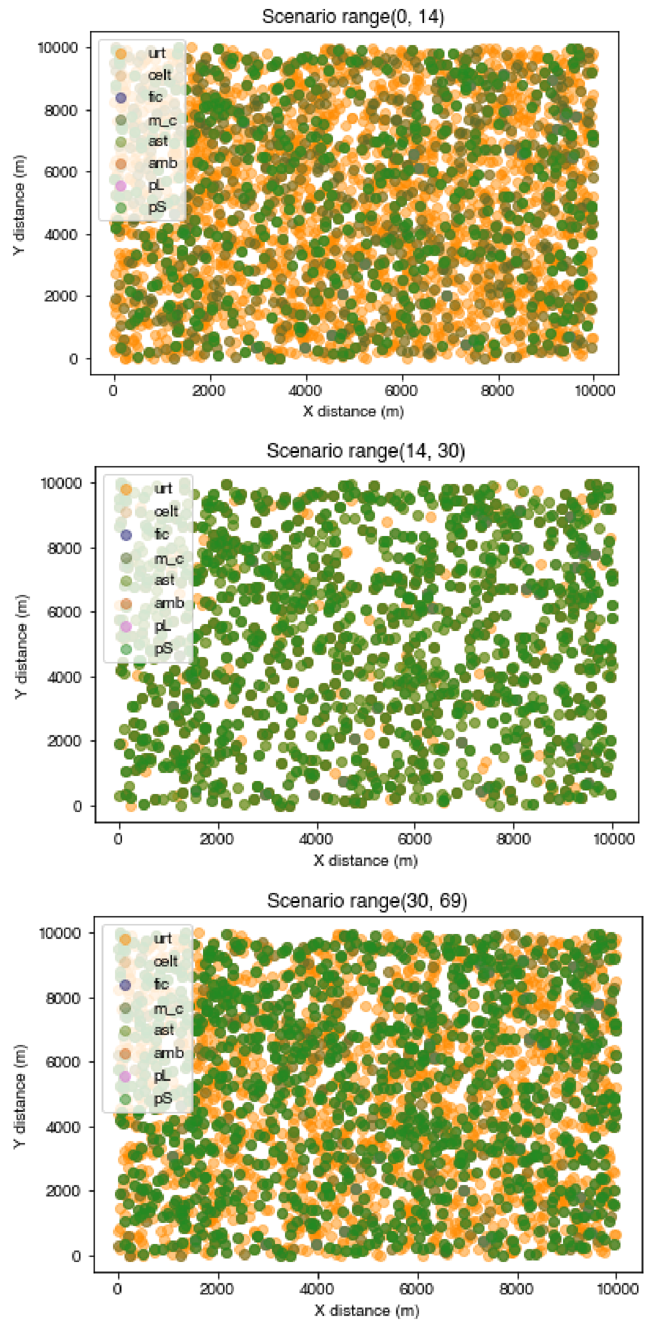


Figure 3. Random Forests A, B, and C (top to bottom)

The model also assumes constant wind and stable stratification across the 10km^2 catchment, and simulates the prevailing winds as Easterly. The degree to which these parameters are well specified could be verified through examining wind data. Unfortunately, it is possible that typical prevailing wind strength and relative humidity at the site was not always in accordance with the modeled assumption of 4 m/s and East to West orientation and RH = 90%. At some sites, the paleoecological variation in wind strength is non-trivial, but it is unclear whether this applies to Petén (Cheng et al. 2020). Additionally, some have argued that pollen release would be better simulated with unstable conditions due to plant preferences for mildly turbulent conditions precluding wind release (Timerman and Barrett 2019).

Results & Conclusions

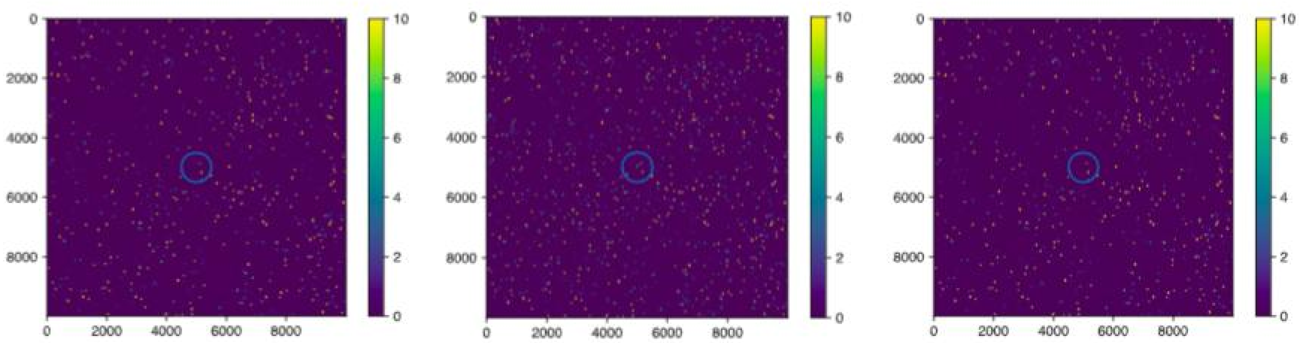


Figure 4. Composite plume plots for scenarios A (left), B (middle), and C (right), x and y axis labels indicate array indices with scale 1index = 1km, color map gives concentrations in u_g/m^3.

Scenario	Forest (modeled)	Forest (actual)	Weeds (modeled)	Weeds (actual)
A	0.230346	0.452857	0.026206	0.122143
B	0.155244	0.220000	0.126342	0.255625
C	0.249434	0.431795	0.000755	0.150769

Table 2. Simulated pollen abundance results and true pollen abundance calculated from the core

Scenario	Modeled/Actual Ratio (Forest)	Modeled/Actual Ratio (Weeds)
A	0.508650	0.214551
B	0.705653	0.494247
C	0.577668	0.005005

Table 3. Fraction of modeled to actual pollen abundances in Laguna Ek'Naab for weed and forest taxa groupings

As indicated by Tables 2 and 3, the Gaussian plume implementation for Laguna Ek'Naab produced poor predictions of true pollen deposition. Considering the lack of parametrization of key variables including stability and particle deposition velocity, and the limited number of model runs conducted, this is unlikely to be representative of true dispersal. Fractions less than one seen in Table 3 indicate that the model underpredicts the true pollen deposition. The most likely reason for this is limitations of the present model in accurately capturing pollen transport to scale. Interestingly, model performance may also suffer in instances when the abundance of the taxa considered is low. This is apparent in the modeled/actual ratio of weedy taxa in Scenario C. Issues of data abundance might be addressed by including more time scenarios, or finding another metric besides the mean to calculate abundance since the mean of relative abundance for a period tends to be smaller than the median in this dataset. Interestingly, across taxa groups and across scenarios, the root mean squared error is less than 0.2. Yet due to the single model run considered for each scenario, this is insufficient for claiming significant results.

Going forward, I would like to change the depositional portion of the model by incorporating the parameters recommended by Jackson and Lyford including deposition velocity, and perhaps adjust to a Lagrangian scheme. I would also like to parametrize the variance of pollen flux and size within a species, and complete further research on the potential for longer distance transport at this site. An additional consideration would be topography, seeing as lakes occur at low points relative to surrounding vegetation and height above lake-level affect pollen collection. Lastly, some have argued that the preference of plants for dispersal in high particular weather conditions may lead unstable stratification scenarios to produce better results, so this too should be parameterized (Montoya-Pfeiffer et al. 2019).

Acknowledgements

Thank you to Professor D. Wahl and collaborators, whose data this project was dependent on. Thank you to D. Krasheninnikov for technical support and F. Walsh for descriptive explanations of depositional physics. Lastly, thank you Professor Baldocchi for the opportunity to study biometeorology and improve my modeling skills.

<u>Word Count: 2299 (~9 pages double spaced excluding figures)</u>

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