Geophysical transport structure and ecology: challenges and opportunities

Shane Ross

Joint work with David Schmale, Amir BozorgMagham, Binbin Lin, A.J. Prussin, Phanindra Tallapragada, Shibabrat Naik

Virginia Tech

Sep, 8 2002
Invasive species riding the atmosphere

Hurricane Ivan (2004) brought new crop disease (soybean rust) to U.S.

From Rio Cauca region of Colombia

Red=infected US regions
Invasive species riding the atmosphere

Hurricane Ivan (2004) brought new crop disease (soybean rust) to U.S.

From Rio Cauca region of Colombia

Cost of invasive organisms is **$137 billion** per year in U.S.
Food supply concerns, bioterrorism

Wheat scientists seek to slow crop fungus in Africa, Asia

* Stem rust, originating in Uganda, spreads to Yemen, Iran

By Alister Doyle

OSLO, Aug 31 (Reuters) - Wheat experts are stepping up monitoring of a crop disease first found in Africa in 1999 to minimise the spread of a deadly fungus that is also a threat in Asia, experts said on Friday.

A "Rust-Tracker", using data supplied by farmers and scientists, could now monitor the fungus in 27 developing nations across 42 million hectares (103 million acres) of wheat - an area the size of Iraq or California.

"It's the most serious wheat disease," Ronnie Coffman, vice-chair of the Borlaug Global Rust Initiative (BGI), told Reuters ahead of a meeting of wheat experts in Beijing from Sept. 1-4.

"If it gets started...it's like a biological firestorm," he said. Experts will review progress in combating the disease, with fungicides and 20 new resistant varieties developed in recent years.

THE THREAT OF PLANT PATHOGENS AS WEAPONS AGAINST U.S. CROPS

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Key Words agricultural vulnerability, biological weapons, bioterrorism, crop biosecurity, plant disease invasion, plant disease persistence and spread, risk analysis

Abstract The U.S. National Research Council (NRC) concluded in 2002 that U.S. agriculture is vulnerable to attack and that the country has inadequate plans for dealing with agricultural bioterrorism. This article addresses the vulnerability of U.S. crops to attack from biological weapons by reviewing the costs and impact of plant diseases on crops, pointing out the difficulty in preventing deliberate introduction of pathogens and discovering new disease outbreaks quickly, and discussing why a plant pathogen might be chosen as a biological weapon. To put the threat into context, a brief historical review of anti-crop biological weapons programs is given. The argument is made that the country can become much better prepared to counter bioterrorism by developing a list of likely anti-crop threat agents, or categories of agents, that is based on a formal risk analysis; making structural changes to the plant protection system, such as expanding diagnostic laboratories, networking the laboratories in a national system, and educating first responders; and by increasing our understanding of the molecular biology and epidemiology of threat agents, which could lead to improved disease control, faster and more sensitive diagnostic methods, and predictions of disease invasion, persistence, and spread following pathogen introduction.

INTRODUCTION

Using [biological weapons] to attack livestock, crops, or ecosystems offers...
Microbes ride in clouds, catalyze rain
Plant pathogens linked to water cycle

What you grow and where affects climate (Cindy Morris, INRA)
Atmospheric transport of microorganisms

e.g., *Fusarium* fungal spores

- Spore production, release, escape from surface
- Long-range transport (time-scale hours to days)
- Deposition, infection efficiency, host susceptibility

Schmaler & Bergstrom [2003], Trail et al. [2005]
Atmospheric transport of microorganisms

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Aylor [1999]
Atmospheric transport of microorganisms

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Isard & Gage [2001], Tallapragada, Ross, Schmale [2011]
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Atmospheric transport of microorganisms

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Deposition patterns can be patchy

Aylor [1999]
David Schmale
aerial sampling:
40 m – 400 m altitude
autonomous unmanned
aerial vehicles

Samples collected over 10-30 minute intervals
at constant elevation above ground level
Count spores, identify down to level of species

UAVs and ground-level sampler → Colonies of Fusarium → Single-spored cultures

- PCR, sequencing, and BLAST searches against FUSARIUM-ID and GenBank
- Morphology-based verification

![Sampling rate chart](chart.png)

- F. armeniacum
- F. avenaceum
- F. circinatum
- F. fujikuroi
- F. graminearum
- F. lactis
- F. lateritium
- F. oxysporum
- F. proliferatum
- F. sambucinum
- F. sporotrichioides
- F. verticillioides
- F. babinda/equiseti-like
Concentration of *Fusarium* spores (number/m$^3$) for samples from 100 flights conducted between August 2006 and March 2010.
Sources are unknown

If sources were known, could model plume
Sources are unknown

Plume changes directions with the wind
Sources are unknown

We are sampling from many sources

We are sampling a superposition of plumes from various distant sources (e.g., diseased fields)

e.g., can imagine ‘invisible’ smoke plumes
Sources are unknown

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Concentration of *Fusarium* spores (number/m$^3$) for samples from 100 flights conducted between August 2006 and March 2010.
Fluctuations in fungal spore concentration

Concentration of *Fusarium* spores (number/m$^3$) for samples from 100 flights conducted between August 2006 and March 2010.

Lin et al. [2012]
Punctuated changes in fungal spore concentration

Concentration of *Fusarium* spores (number/m$^3$) for samples from 100 flights conducted between August 2006 and March 2010.
A classic punctuated change

Define punctuated change as low probability events (assuming Poisson process), e.g., changes which have probability < 1%
Punctuated changes: How to understand cloud edges?

Detected concentration of Fusarium at sampling location
Punctuated changes: How to understand cloud edges?

Detected concentration of Fusarium at sampling location

Sampling location

time
Punctuated changes: How to understand cloud edges?
Punctuated changes: How to understand cloud edges?
Atmospheric transport network

LCS, repelling (orange) and attracting (blue)

Atmospheric Superhighway, a skeleton of large-scale horizontal transport

Relevant for large-scale spatiotemporal patterns of pollution but also biological agents

orange = repelling LCSs, blue = attracting LCSs
Curtain-like partitions moving over landscape
Mesoscale to synoptic scale motion

- Consider first 2D motion, then fully 3D
- Quasi-2D motion (isobaric) over timescales of interest, < 12-24 hrs, given by fungal spore viability

Using wind fields from NOAA
Identify ‘atoms’ of transport bounded by LCS

- Coherent atmospheric filaments or vortices which mix little with surroundings, analogous to ocean eddies
- Temporarily isolated sub-systems
Volumes of differing spore composition partitioned by LCS

Our unmanned aerial vehicles (UAVs) are usually sampling one side or the other.
Filament with high pathogen values ‘sandwiched’ by LCS
Filament with high pathogen values ‘sandwiched’ by LCS
Filament with high pathogen values ‘sandwiched’ by LCS

12:00 UTC 1 May 2007

15:00 UTC 1 May 2007

18:00 UTC 1 May 2007
Microbe fluctuations associated with LCS

- Punctuated change was associated with a LCS passage >70% of the time

- Airborne biological agent concentrations can provide a proxy for measuring Lagrangian transport structure

Tallapragada, Ross, Schmale [2011] *Chaos*
Sampling biological tracers at a fixed location

- Sampling point: Virginia Tech campus
- Sampling times: 8AM – 8AM, Sep 29 & 30, 2010
- Integration time: - 24 h.

Backward trajectory of particles, time delay = 1h
Sampling biological tracers at a fixed location

24 hour back-trajectories

Sourceline of sampled points

Distance between adjacent points along sourceline

Distance between the initial position of the sampled particles

Distance between adjacent points along sourceline
Sampling on either side of a LCS

\[ \delta s(t_0 + T) \approx \lambda_{\text{max}}^{1/2} \left[ C_{t_0}^{t_0+T}(x_0) \right] u(x_0, t_0) \delta t \]

Back trajectories with attracting LCS

Red: sample time: 1315 UTC
Blue: sample time: 1415 UTC
Green: sample time: 1515 UTC

Movie is showing time backwards

Back-trajectories shown
Effect of turbulence

Deterministic back-trajectory

24 hrs
12 hrs
6 hrs
Effect of turbulence

Comparing turbulent and deterministic back-trajectory
FTLE including sub-grid scale turbulence

Deterministic

incl. turbulent diffusion

BozorgMagham, Ross [2013]
FTLE including sub-grid scale turbulence

Ensemble average

Standard deviation

BozorgMagham, Ross [2013]
Forecasting atmospheric LCS

Wind field errors are not small or localized in time

BozorgMagham, Ross, Schmale [2013] Physica D
Forecasting atmospheric LCS

Using an ensemble forecasting approach

Ensemble average

Standard deviation

BozorgMagham, Ross [2013]
Forecasting atmospheric LCS

Forecasting an LCS passage time

Can correctly forecast within 2 hours 60% of the time

BozorgMagham, Ross [2013]
Practical application: early warning systems

LCS or other transport methods could help inform farmers regarding possible zones of disease spread.
Lagrangian transport structure and ecology

- Could provide insight to spatiotemporal data and models in ecology
- Role of rare transport events
- Bifurcations changing the global transport structure (e.g., due to climate change)
- Universal principles for fluid regimes: oceans, rivers, lakes, ...
In aeroecology, concerns about likely pathways or persistent barriers.
Aeroecology and the global transport of desert dust

Lagrangian bridge connecting distant ecosystems

Kellogg, Griffin [2006]
Connectivity between vastly separated ecosystems

Chlorophyll transport in the Gulf of Mexico

Chlorophyll as a tracer of biological advection and connectivity

Toner, Kirwan, Poje, Kantha, Muller-Karger, Jones [2003]
Connectivity and mixing in Southern California Bight

Relevant for marine ecosystem, larval transport, nutrient mixing

Applications of transition matrices, transfer operator, graph theoretic approaches?
Ghost rod stirring around islands?

Mitarai, Siegel, Watson, Dong, McWilliams [2009]; Harrison, Siegel, Mitarai [2013]
Forecasting sudden *ecosystem* changes

Application of, e.g., the LCS-core analysis of Olascoaga & Haller [2012] to predict rare biological incursions, drastic changes in connectivity?

Provide early warning of rapid long-distance dispersal events
Main Papers:


- Lin, BozorgMagham, Ross, Schmale [2013] Small fluctuations in the recovery of fusaria across consecutive sampling intervals with unmanned aircraft 100 m above ground level. *Aerobiologia* 29(1), 45-54.


