Crop health and its impact in rapidly changing agricultural contexts: the case of rice in Asia

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with contributions from
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Facts

• 2011 is unique in human History:
• for the first time, the global population will reach $7 \times 10^9$ people;
• for the first time, more than half the world’s population will live in cities;
• and for the first time, $1 \times 10^9$ human beings will live below the threshold of poverty.
Questions

• What is the role of agricultural research in this context?
• more specifically: what can be the role of plant protection?
• further: what should be the role of plant disease epidemiologists?
• back to the first question: how to connect plant disease epidemiology and plant protection, with the role that agronomic research at large should play?
Outline of the presentation

- Overall current context: the status of rice input-output (and crop health) system
- Questions that plant disease epidemiologists address
- Epidemiological modelling: introducing RICEPRE
- One application of epidemiological modelling: quantitative effects of components of resistance
- Modelling and mapping potential epidemics, globally
- The challenges ahead
0 – Overall current context: the status of rice input-output (and crop health) system

(what follows in this section is a summary of surveys conducted in 2009 and 2010 on 374 farmers’ fields in India, Bangladesh, Indonesia, Thailand, Vietnam, and the Philippines, at a range of sites in each country)
total mineral fertilizer use, by country

MF: mineral fertilizer input, kg per ha
accumulated water shortage, by country

DSCUM: accumulated occurrence of water shortage during a cropping season

- Bangladesh
- India
- Indonesia
- Philippines
- Thailand
- Vietnam

COUNTRY$
pesticide use, by country

IU: insecticide use, number of applications per cropping season
HU: herbicide use, number of applications per cropping season
FU: fungicide use, number of applications per cropping season
actual (harvested) yield, by country

Yield: actual (harvested) yield, tons per ha

YIELD

COUNTRY

Bangladesh | India | Indonesia | Philippines | Thailand | Vietnam
actual (harvested) yield, by country and season

Yield: actual (harvested) yield, tons per ha
disease injuries, by country in the rainy season

BLB: bacterial blight, area under disease progress curve; IB: leaf blast, area under disease progress curve; BS: brown spot, area under disease progress curve; SHB: sheath blight, maximum incidence; FSM: false smut, maximum incidence; NB: neck blast, maximum incidence; RSD: ragged stunt disease, maximum incidence.
disease injuries, by country in the dry season

BLB: bacterial blight, area under disease progress curve; IB: leaf blast, area under disease progress curve; BS: brown spot, area under disease progress curve; SHB: sheath blight, maximum incidence; FSM: false smut, maximum incidence; NB: neck blast, maximum incidence; RSD: ragged stunt disease, maximum incidence.
weeds and animal pest injuries, by country in the rainy season

WA, WB: weed infestation above and below the canopy area under weed infestation progress curve; DH: dead hearts (stem borers), maximum incidence; WH: white heads (stem borers), maximum incidence; RT: rat injury maximum incidence; BPH: brown planthopper maximum population size per tiller.
weeds and animal pest injuries, by country in the dry season

WA, WB: weed infestation above and below the canopy area under weed infestation progress curve; DH: dead hearts (stem borers), maximum incidence; WH: white heads (stem borers), maximum incidence; RT: rat injury maximum incidence; BPH: brown planthopper maximum population size per tiller.
some inputs and actual yield output, by seasons

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>MF</th>
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<th>HU</th>
<th>FU</th>
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some disease injuries, by seasons

**Results for SEASON$ = RS**

<table>
<thead>
<tr>
<th></th>
<th>BLBA</th>
<th>LBA</th>
<th>BSA</th>
<th>SHBX</th>
<th>FSMX</th>
<th>NBX</th>
<th>RSDX</th>
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**Results for SEASON$ = DS**

<table>
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<th>LBA</th>
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<tr>
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some injuries caused by weeds and animal pests, by seasons

Results for SEASON$ = RS

<table>
<thead>
<tr>
<th></th>
<th>WAA</th>
<th>WBA</th>
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<th>WHX</th>
<th>RTX</th>
<th>LFA</th>
<th>BPHX</th>
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<td>1.156</td>
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<td>0.999</td>
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Results for SEASON$ = DS

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<th>RBBX</th>
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<td>2.757</td>
<td>1.191</td>
<td>187.297</td>
<td>43.363</td>
<td>1.226</td>
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<tr>
<td>SE</td>
<td>77.817</td>
<td>80.443</td>
<td>0.354</td>
<td>0.444</td>
<td>0.233</td>
<td>18.029</td>
<td>5.159</td>
<td>0.526</td>
</tr>
</tbody>
</table>
Overall current context: summary

- the level of mineral fertilizer input in the region ranges, on average, between 100 and 200 kg.ha\(^{-1}\). This is 2 to 3 times more than 10 years ago.
- most fields, even in irrigated environments, encounter one period of water shortage during the cropping season.
- the level of pesticide use has doubled to tripled in ten years.
- and yet, the yield levels have remained the same, roughly 4 tons.ha\(^{-1}\), without even clear-cut differences between the dry and the rainy season.
- most levels of injuries have increased, some of them considerably.
- several crop health problem, until recently considered secondary, have become serious concerns: ragged stunt disease, BPH, false smut.
- obviously: the total factor productivity of rice-based agroecosystems has sharply declined over the past ten years; it is constrained by shrinking resources (water, labour).
- declining crop health is both a result and a cause of such imbalances, and compounds the eroding sustainability of these systems.
1 – Questions that plant disease epidemiologists address
Why plant disease epidemiology?

• Importance of plant diseases because of epidemics
• We need to understand epidemics as we know them today
  – to implement effective control tools (incl. HPR)
  – to deploy efficient, durable control tools (involves ecological concepts)
• We need to predict epidemics which will inevitably occur (possibly new diseases) tomorrow
  – global and climate change: labor shortage, natural resources (incl. water scarcity), shortage of land, energy shortage, and local to global trade
  – the above are drivers of agricultural change
  – they affect crop health: (1) the relative importance of diseases is changing, (2) while the factors underpinning epidemics are changing — the underlying mechanisms remain
• There are many plant diseases: need for a framework, for methodology
• To summarize: the problem is so complex, involves so many components and interactions, concerns so many scales, that there is a need for a system’s approach.
System’s based concepts in plant disease epidemiology can

- **Help control epidemics** (good)
  - host plant resistance - 1 (partial HPR)
  - host plant resistance - 2 (deployment: complete HPR, partial HPR; over space and/or time)
  - tactical decisions: crop (health) management

- **Help prevent epidemics** (better)
  - host plant resistance - 3 (complete HPR)
  - disease exclusion techniques (e.g., seed health)

- **Contribute to a system’s based framework**:
  - so many components (incl. diseases), interactions, and scales (e.g.: plant → field → landscapes, or: farmer → local market → national and international markets);
  - some diseases are barely known, biologically: basic research is needed, but must be prioritized
Typical issues plant disease epidemiologists address

1. Why do some diseases take off, whereas others do not?
2. Why do some strains, races, or pathotypes die out, some coexist, and others come to dominate pathogen populations?
3. How does the inherent variability associated with epidemics translate into risk?
4. Given that new infections occur at the small scale but epidemics are manifest at the large scale, how can we scale from individual to population behavior?
5. How can this information be used to identify control methods?
6. How can this information be used to optimize the efficient deployment and durability of control methods?
7. How does the way we grow and protect our crops or manage our natural and seminatural environment affect these outcomes?

2 – Epidemiological modelling: introducing EPIRICE
Diversity of rice diseases (pathogens, biological cycles)

- Bacterial leaf blight
- Brown spot
- Leaf blast
- Neck blast
- Sheath blight
- Sheath rot
- False smut
- Tungro

Number of publications in epidemiology*

* Journal articles, books, and book chapters in CAB Abstracts (1973- current)
Shapes of a few rice disease epidemics

- **Brown spot**: Disease severity (fraction leaf surface diseased)
- **Bacterial blight**: Disease incidence (fraction of leaves diseased)
- **Sheath blight**: Disease incidence (fraction of tillers diseased)
- **Tungro**: Disease incidence (fraction of plants diseased)
the SEIR model

• SEIR = Suscepts, Exposed, Infectious, Removed
• or (Plant Pathology):
  – H, Healthy sites
  – L, Latent sites
  – I, Infectious sites, and
  – P, post-infectious sites
• One key rate: infection rate
• Two delays: latency period, infectious period
the SEIR model: applications

• medical epidemiology
  – measles
  – HIV
  – influenza
  – tuberculosis

• animal epidemiology
  – Pseudorabies virus in pigs
  – Mouse typhoid

• computer viruses?

• … and botanical epidemiology
infection rate (RI) - equation

\[ \frac{dL}{dt} = RI = R_c I C^a \]

- \( L \): latent sites; \( I \): infectious sites
- \( R_c \): basic infection rate corrected for removals = number of new infections, per unit time, per infectious site (I)
- \( C \): “correction factor” = fraction of healthy sites (H), relative to the total number of sites in the system
- \( a \): disease aggregation coefficient
infection rate (RI) – over time

\[ \frac{dL}{dt} = RI = R_c I C^a \]

<table>
<thead>
<tr>
<th>parameter</th>
<th>early season</th>
<th>mid-season</th>
<th>late season</th>
</tr>
</thead>
<tbody>
<tr>
<td>I fraction infectious</td>
<td>v. small</td>
<td>small</td>
<td>med.-large</td>
</tr>
<tr>
<td>C^a fraction healthy,</td>
<td>v. large</td>
<td>large</td>
<td>med.-small</td>
</tr>
<tr>
<td>accounting for aggregation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RI v. small</td>
<td>v. small</td>
<td>larger</td>
<td>smaller</td>
</tr>
</tbody>
</table>
some additional ‘details’

• growth of the host = crop growth = growth of healthy sites
• senescence = physiological (or/and) pathological
• additional effects (on rate of infection only):
  – plant age (variable susceptibility)
  – temperature
  – canopy moisture
spatial scales of plant disease epidemics

- local infections on the foliage
  - 1 lesion = a small fraction of leaf area
  - ex.: leaf blast; brown spot

- rapidly expanding infections on the foliage
  - 1 lesion = a leaf
  - ex.: bacterial blight

- infections affecting entire tillers
  - 1 lesion = a tiller
  - ex.: sheath blight

- systemic infections
  - 1 lesion = a plant
  - ex.: tungro
scaling the model structure to address different diseases: definition of sites

• a site (a lesion) = a unit of host (plant) tissue where the pathogen develops and produces new dispersal units

• sites ↔ levels of hierarchy chosen: depend on the disease:
  – portion of leaf area: leaf blast, brown spot
  – a leaf: bacterial blight
  – a tiller: sheath blight
  – a plant: tungro
the SEIR model in plant pathology

the SEIR model in plant pathology

SEIR – system of differential ordinal equations

\[
\frac{dH}{dt} = - \beta HI
\]

\[
\frac{dL}{dt} = \beta HI - \omega L
\]

\[
\frac{dI}{dt} = \omega L - \mu I
\]

\[
\frac{dR}{dt} = \mu I
\]

- \(H\) : number of healthy individuals
- \(L\) : number of latent individuals
- \(I\) : number of infectious individuals
- \(R\) : number of post-infectious (removed) individuals
- \(1/\omega\) : mean latent period
- \(1/\mu\) : mean infectious period
- \(\beta\) : per capita transmission rate (new diseased individuals per diseased individual per healthy individual per unit time).
A few rice disease epidemics simulated

Brown spot

Bacterial blight

Sheath blight

Tungro
A few rice disease epidemics simulated

<table>
<thead>
<tr>
<th>Disease</th>
<th>Healthy</th>
<th>Latents</th>
<th>Infectious</th>
<th>Removed</th>
<th>Total diseased</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brown spot</td>
<td></td>
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<td>Bacterial blight</td>
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<td>Tungro</td>
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</table>

<table>
<thead>
<tr>
<th>Disease</th>
<th>Number of sites</th>
<th>Disease intensity (%)</th>
<th>Time (DACE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brown spot</td>
<td></td>
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</tr>
<tr>
<td>Tungro</td>
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</tbody>
</table>

Graphs showing the progression of disease over time for each respective disease.
3 – One application of epidemiological modelling: quantitative effects of components of resistance
Simulated effects of components of partial resistance to leaf blast

definition of parameters
relative resistance (rr) parameters:

\[ \begin{align*}
  \text{s} &= \text{susceptible check} \\
  \text{t} &= \text{test variety} \\
  0 \ (s) &\leq \text{RR}(t) \leq 1 \ (\text{complete resistance}) \\
  \text{rr}_E &= \frac{E_t}{E_s} \\
  \text{rr}_N &= \frac{S_t}{S_s} \\
  \text{rr}_i &= \frac{i_t}{i_s} \\
  \text{rr}_p &= 1 - \left( \frac{p_t}{p_s} \right)
\end{align*} \]

Note: Challenge and opportunity of linking relative resistance (rr) parameters to QTLs and genes, e.g., in the case of leaf blast, where partial resistance is in the process of being well characterized (Ballini et al., 2008. A genome-wide meta-analysis of rice blsat resistance and quantitative trait loci provides new insights into partial and complete resistance. Molecular Plant-Microbe Interactions 21:859-868).
Simulated effects of components of partial resistance to leaf blast

Relative resistance for latency period

Relative resistance for infectious period

Relative resistance for infection efficiency and effective propagule production

$rr_p$, $rr_i$, $rr_E$ and $rr_N$
Simulated effects of aggregation on sheath blight epidemics

definition of parameter

\( a \): coefficient for disease aggregation (i.e., pathogen and host, and infection)

\( a = 1 \) (default): random distribution of diseased sites amongst host sites (each site has an even chance of becoming infected).

\( a > 1 \): disease aggregation within a landscape of susceptible suscepts

e.g., Sheath Blight: \( a \gg 1 \) (varies with crop establishment and disease spread)
Simulated effects of aggregation on sheath blight epidemics
Simulated effects of onset time on tungro epidemics

definition of parameters

onset = time of onset of epidemic (date of establishment of the 1\textsuperscript{st} infection), relative to crop establishment date.
Simulated effects of onset time on tungro epidemics

Effect of disease onset:
- Onset = 15
- Onset = 25
- Onset = 35
- Onset = 45
4 – Modelling and mapping potential epidemics, globally
Potential epidemics

• **We need to know**
  1. impact of what could happen without control;
  2. extent of potential epidemics;
  3. the potential effects of global and climate change, and thus
  4. the potential effects of shifts in agricultural practices leading to new crop health contexts

• **Why?**
  5. control options take years to develop (e.g., breeding HPR ~ 10 yrs)

• **How?**
  6. simulation modelling + mapping and GIS
  7. (simulations and map are no substitute, but complement, ground truth: “eyes in the fields”)
Avg 1997-2008

Bacterial blight

Std 1997-2008
5 – The challenges ahead
Global and climate changes and their effects

- Global (including climate) change represents a clear and present danger for agricultural sustainability
- It does affect very strongly crop health, in general, plant diseases, in particular
- The effects of poor crop health are omnipresent, very heavy, and need to be considered in sustainable agricultural systems,
- while ‘new’ disease emerge (re-emerge) as shifts in production systems take place.
Global and climate change represent a clear and present danger for agricultural sustainability.

**Current:**
What we know

- Production Situations
  - Bio-Physical effects on Processes
  - Injury Profiles

**Global Climate Change**

Indirect Effect: Shirking Resources (water, land, labor, energy)

- New Production Situations
  - Direct Effects on Cycles
  - Altered Bio-Physical Processes
  - New Injury Profiles

**Future**
What needs to be understood to guide improved crop health management, including HPR
They do affect very strongly crop health, in general, plant diseases, in particular...
The effects of poor crop health are omnipresent, very heavy, and need to be considered in sustainable agricultural systems.

In rough, average terms, **chronic** losses to diseases, insects, and weeds represent 10, 5, and 20% of the attainable yield to diseases, insects, and weeds, respectively.
while ‘new’ disease emerge (re-emerge) as shifts in production systems take place.
while ‘new’ disease emerge (re-emerge) as shifts in production systems take place.