Linking crops (models) with pest and diseases

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Outline

- Why linking crop models with pest and disease (models)
- Significance of crop losses from P&D
- Examples for modelling
- Data requirements
- Potential data sources
Why it is important to consider P&D within crop models (and vice versa)?

- Increasing world population as well as changing consumers' diets require a significant increase of food production per area since suitable global land area to produce food is limited and cannot be extended without dramatic ecological impacts.
- Especially in the industrial and emerging countries more and more productive areas are lost by sealing.
- To cope world's food demand a doubling of the crop yields per area until 2050 is required.
- This corresponds to an annual increase of yield per hectare by ~2.5%.
- Considerable yield gaps exist in many parts of the world.
- Pest and diseases are contributing to the yield gap significantly.
- An integrated pest and disease management and smart pesticide application is required to reduce impacts on humans and environment.
Global realisation of attainable yields

Müller et al. 2012, Nature
Global yield gap of rainfed wheat

Global Yield Gap Atlas 2017
Assessment of the relative contribution to yield gaps in maize

Figure 3.5 **Maize**: Relative contribution of five production constraints, i.e. sub-optimal availability of water, nutrients, crop protection, labour/mechanisation and/or knowledge, to the gap between current and potential yields in different parts of the world.

Hengsdijk & Langeveld 2010

10-20% for P&D
Assessment of the relative contribution to yield gaps in potatoes.

Figure 3.7 Potato: Relative contribution of five production constraints, i.e. sub-optimal availability of water, nutrients, crop protection, labour/mechanisation and/or knowledge, to the yield gap in different parts of the world.

Hengsdijk & Langeveld 2010
High uncertainty of yield loss assessment

Expert assessment vs. assessment based on yield observations (Oerke, 1999)

Hengsdijk & Langeveld 2010

Assessments are rarely based on modelling
Fig 5. Location specific agricultural input and management strategies as required in different parts of the world to achieve high-input potential yields in addition to adequate fertilizer application (F). The strategies consist of soil quality management (S), managing accessibility to markets (A), weather induced yield variability management (V), and management of pests, diseases, and weeds (P). The different management strategies can have combinations of the individual elements (F, S, A, V, and P).

doi:10.1371/journal.pone.0129487.g005

Prahan et al. 2015
## Table 1. Regional overview of additional crop calories that can be produced on rain-fed cultivated land by closing yield gaps with various management strategies in addition to adequate fertilizer application (F).

<table>
<thead>
<tr>
<th>Regions</th>
<th>F</th>
<th>S</th>
<th>A</th>
<th>AS</th>
<th>V</th>
<th>VA</th>
<th>VAS 10^12 kcal/yr</th>
<th>P</th>
<th>PS</th>
<th>PA</th>
<th>PAS</th>
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<td>Australia &amp; New Zealand</td>
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<td>20.8</td>
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The strategies consist of soil quality management (S), managing accessibility to markets (A), weather induced yield variability management (V), and management of pests, diseases, and weeds (P). The different management strategies can have combinations of the individual elements (F, S, A, V, and P). These values were estimated by summing up the differences between the current and the high-input potential crop calorie production by region and by the required management strategy.

Prahan et al. 2015
What would be the benefit of a better (model based) estimation of crop loss from P&D?

- Better understanding of pest and disease drivers to derive management options
- Management decisions based on economic cost-benefit analysis
- Simulation of what-if scenarios
- Reduced impact on human health and environment due to smart pesticide application.
- Assessment of P&D impact on crop production under changing boundary conditions, e.g. climate change
Crop models are valuable tools to assess potential yields and yield gaps

However, the models have limitations:
“While highly suited for optimal management situations they rapidly lose value when complex yield limiting and yield reducing factors occur that provoke a wide range of remedial management; such yield gap aspects almost never feature in the models.”

De Bie, 2002
Crop models and models for several pests and diseases are already existing.

- Crop models are considering water and nutrient limitations, but rarely damages from pest and diseases.
- There are models describing the pest and disease development depending on weather variables.
- Interdependences between crops and P & D are often not considered or rely on observed data and empirical relations.
- P & D models are mainly used to initiate pesticide application, rarely for crop loss assessment.
- However, under changing climate empirical relations between crops, pest and diseases, but also between P & D and their antagonists may change.
- Interactions are complex.
- This requires to link crop models and P&D models for a better assessment of future impact.
Examples of linking crop models to P & D models

Going back in history

Computer-Aided Modelling and Simulation of the Winter Wheat Agroecosystem (AGROSIM-W) for Integrated Pest Management

Papers on agroecosystem modelling presented in the frame of the International Symposium
“Plant Protection Problems in High-Intensity Cereal Growing”
arranged by
Plant Production Section of Martin Luther University
Halle-Wittenberg
and Academy of Agricultural Sciences of the GDR
in Halle, GDR, from 26 to 30 September, 1984

1986

AKADEMIE DER LANDWIRTSCHAFTSWISSENSCHAFTEN
DER DEUTSCHEN DEMOKRATISCHEN REPUBLIK
Damages caused by pest and diseases and their link to crop models

Matthäus et al. 1986
Damages caused by pest & diseases and their link to a crop model

Matthäus et al. 1986
Simulated yield loss caused by cereal aphids

Grain yield loss by *Macrosiphum* infestation (full line) in dependence on tact of pesticide application; abundance maximum of *Macrosiphum* (dashed line) in dependence on tact of pesticide application; and abundance of *Macrosiphum* without any pesticide application (dashed dotted line)

Ebert et al. 1986
There is more than only crop-pest relation

Population dynamics of the cereal aphid is closely associated with the development of the wheat crop

Natural antagonists – predators, parasites - strongly influence abundance dynamics of the cereal aphids
Simulated yield loss caused by a complex infestation

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Fig. 5: Influence of complex infestation on grain yield. Weather data for 1980

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Ebert et al. 1986
# Interactions between crop, P & D, and predators

**Survey of the interaction between insect pests, diseases, predators and crop plant**

<table>
<thead>
<tr>
<th>Pests and diseases</th>
<th>Pest-to-crop effects</th>
<th>Crop-to-pest effects</th>
<th>Crop-to-predator effects</th>
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<tbody>
<tr>
<td></td>
<td>Effects on matter flows (primary crop damage)</td>
<td>Effects on processes (secondary crop damage)</td>
<td>Effects on processes by limitations of resources</td>
</tr>
<tr>
<td>Mildew (Erysiphe graminis)</td>
<td>Extraction of assimilates from resource AR&lt;sub&gt;T&lt;/sub&gt;</td>
<td>Acceleration of wheat yellowing</td>
<td>Lower infection and sporulation rates through limited green biomass</td>
</tr>
<tr>
<td>Leaf beetles (Oulema spp.)</td>
<td>Feeding on green biomass from resource GR&lt;sub&gt;T&lt;/sub&gt;</td>
<td>Higher photosynthetic rate through more light in the crop</td>
<td>Higher mortality rates through limited food supply</td>
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<tr>
<td>Cereal aphids (Macrosiphum avenae)</td>
<td>Phloem sap sucking from resource PR&lt;sub&gt;T&lt;/sub&gt;</td>
<td>Lower photosynthetic rate through excretion of honey dew</td>
<td>Higher mortality rates and reduced reproduction through limited phloem sap supply</td>
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<table>
<thead>
<tr>
<th>Predator</th>
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<th>Pest-to-predator effects</th>
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<td>Ladybirds (Coccinellidae)</td>
<td>Feeding on aphids from <em>Macrosiphum</em> resource</td>
<td>Increase of individual feeding rate in dependence on food supply</td>
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</table>

**additional problem:** Genetic mutation changes behavior of P&D much faster due to multiple generations/year

**Ebert et al. 1986**
Required steps to involve pest and diseases in crop models

1. Surveys in farmers' fields
   - Production situations to consider
   - Selection of injuries (diseases, pests) to include

2. Field experiments: injuries and yield losses
   - Experimental factors: production situations and injury profiles
   - Experimental designs, production situations and injuries to include
   - Statistical yield loss models

3. Crop growth model with damage mechanisms
   - Processes
   - Parameters
   - Existing modelling structures
   - Published damage mechanisms and parameters

4. Model verification: Production situations and Injury profiles
   - Parameterized model

5. Field experiment for model evaluation
   - Observed growth, yield, yield losses

6. Model evaluation
   - Verifield model

Donatelli et al. 2017
### Table 8.1. Damage mechanisms of crop pest injuries

<table>
<thead>
<tr>
<th>Damage mechanism</th>
<th>Physiological effect</th>
<th>Effect in a crop growth model</th>
<th>Examples of pests</th>
</tr>
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<tbody>
<tr>
<td>Light stealer</td>
<td>Reduces the intercepted radiation</td>
<td>Reduces the green LAI</td>
<td>Pathogens producing lesions on leaves</td>
</tr>
<tr>
<td>Leaf senescence</td>
<td>Increases leaf senescence, causes defoliation</td>
<td>Reduces the biomass of leaves by increasing the rate of leaf senescence</td>
<td>Foliar pathogens such as leaf-spotting pathogens, downy mildews</td>
</tr>
<tr>
<td>Tissue consumer</td>
<td>Reduces the tissue biomass</td>
<td>Outflows from biomasses of the injured organs</td>
<td>Defoliating insects</td>
</tr>
<tr>
<td>Stand reducer</td>
<td>Reduces the number and biomass of plants</td>
<td>Reduces biomass of all organs</td>
<td>Damping-off fungi</td>
</tr>
<tr>
<td>Photosynthetic rate reducer</td>
<td>Reduces the rate of carbon uptake</td>
<td>Reduces the RUE</td>
<td>Viruses, root-infecting pests, stem-infecting pests, some foliar pathogens</td>
</tr>
<tr>
<td>Turgor reducer</td>
<td>Disrupts xylem and phloem transport</td>
<td>Reduces the RUE, accelerates leaf senescence</td>
<td>Vascular, wilt pathogens</td>
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<tr>
<td>Assimilate sapper</td>
<td>Removes soluble assimilates from host</td>
<td>Outflows assimilates from the pool of assimilates</td>
<td>Sucking insects, e.g. aphids, some planthoppers, biotrophic fungi exporting assimilates from host cells</td>
</tr>
</tbody>
</table>

*Derived from Rabbinge and Vereyken (1980), Rabbinge and Rijsdijk (1981) and Boote et al. (1983).*
Using observed data to link crop models to pest and diseases

- Using observed injury levels as input for crop models via defined damage mechanisms is an appropriate way for retrospective or on-time crop loss assessments.
- This can be useful to explain observed yield gaps and interannual variability of crop production.
- However, an assessment under changing boundary conditions, e.g. climate or management is problematic.
Coincidence of host and pest may change with climate change

Kersebaum & Eitzinger 2009
First exercise to test implementation of P&D injuries in crop models

- Data of the site Jyndevad in Denmark (Lat: 54°54` N, Long: 9° 08 E, Alt: 14 m a.s.l.) are provided for soils, weather and management of a real experiment in 1995/96
- Data of full pesticide treated variant were provided to calibrate on “no P&D affected” attainable yield (rainfed).
- Ideotypes of wheat injury drivers for leaf (brown) rust, septoria tritici blotch, yellow (stripe) rust, and powdery mildew linked to crop phenology were provided by Laetitia Willoquet

Participating models

<table>
<thead>
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<th>Model</th>
<th>Key partner</th>
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<td>HERMES</td>
<td>K. C. Kersebaum</td>
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<td>WOFOST-GT</td>
<td>S: Bregaglio/T. Stella</td>
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<tr>
<td>SSM-WHEAT</td>
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![Graph showing disease severity fraction leaf area covered]
<table>
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<tr>
<th>Damage mechanism</th>
<th>Physiological effect</th>
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<td>Reduces the green LAI</td>
<td>Pathogens producing lesions on leaves</td>
</tr>
<tr>
<td>Leaf senescence</td>
<td>Increases leaf senescence, causes defoliation</td>
<td>Reduces the biomass of leaves by increasing the rate of leaf senescence</td>
<td>Foliar pathogens such as leaf-spotting pathogens, downy mildews</td>
</tr>
<tr>
<td>Tissue consumer</td>
<td>Reduces the tissue biomass</td>
<td>Outflows from biomass of the injured organs</td>
<td>Defoliating insects</td>
</tr>
<tr>
<td>Stand reducer</td>
<td>Reduces the number and biomass of plants</td>
<td>Reduces biomass of all organs</td>
<td>Damping-off fungi</td>
</tr>
<tr>
<td>Photosynthetic rate</td>
<td>Reduces the rate of carbon uptake</td>
<td>Reduces the RUE</td>
<td>Viruses, root-infecting pests, stem-infecting pests, some foliar pathogens</td>
</tr>
<tr>
<td>reducer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turgor reducer</td>
<td>Disrupts xylem and phloem transport</td>
<td>Reduces the RUE, accelerates leaf senescence</td>
<td>Vascular, wilt pathogens</td>
</tr>
<tr>
<td>Assimilate sapper</td>
<td>Removes soluble assimilates from host</td>
<td>Outflows assimilates from the pool of assimilates</td>
<td>Sucking insects, e.g. aphids, some planthoppers, biotrophic fungi exporting assimilates from host cells</td>
</tr>
</tbody>
</table>

*Derived from Rabbinge and Vereyken (1980), Rabbinge and Rijsdijk (1981) and Boote et al. (1983).*
First exercise to test implementation of P&D injuries in crop models

![Graph showing grain yield and yield loss](image1)

![Graph showing LAI max](image2)

![Graph showing relative yield loss](image3)
Injury driver realisation in different models

Severity Septoria

Severity Powdery Mildew

Severity Brown rust

Severity Yellow rust
Step 1b: Calibration of biomass partitioning
Step 1b: Calibration of leaf area index
First exercise to test implementation of P&D injuries in crop models

Step 1b: harmonisation of biomass partitioning and LAI

Differences in crop loss estimation became smaller, but are still very high.

Observed yield loss was in the order of magnitude of 1 t/ha with about 20% severity of septoria and mildew.
Uptake of assimilates by diseases

Assimilate uptake (kg/ha) differs significantly due to different assimilation pools in the models.
Models are the ultimate tool for climate impact assessment ...

..., but observed data are the indispensable backbone of all modelling efforts to:

- Develop, calibrate and validate models at different scales
- Prove model consistency across variables and conditions
- Provide specific inputs for regional and pan-European model assessments with an adequate resolution and accuracy
- Analyze spatio-temporal trends within and across regions
- Test upscaling and downscaling methods
- Identify and simulate complex interactions between variables and impacts
What are requirements to data to link P&D models?

Additional data are required:

- Micro-climate (e.g. leaf wetness, canopy temperature)
  (measured or simulated?)
- Higher temporal resolution of meteorological data (hourly)
- Observations on pest and disease population and development
- Documented losses from protected and unprotected crops
- Observed differences in variety vulnerability
- Many data sets are existing, but not accessible
Current limitations of data

- Observations of injury/damage levels are often not standardized and objective since they are often based on subjective appraisals.
- Limited spatial focus or temporal resolution, which might not provide a representative spot for fields/regions.
- Selective consideration of one or a few pest and diseases.
- Limited background information regarding the production level, plant protection practice or varieties.
Potential data sources

- Manipulated experiments to assess effects of, e.g., fertilization, rainfed/irrigation, CO\textsubscript{2}, tillage

- Data from variety trials or from crop protection agencies with different plant protection levels, which can be linked to site conditions.

- Remote sensing techniques capable to detect and integrate P&D levels at different scales.

- Occurrence and pressure of P&D from citizen science surveys
Assessing crop loss from variety trials

Grain yield winter wheat from variety trial in Germany with and without fungicide

Records usually contain data on sowing, phenology, harvest, fertilization, crop protection, and rating of selected diseases for individual varieties.

Piepho et al. 2014
Example of a citizen science project to classify and monitor crop diseases

Classifying plant diseases with a smartphone-App (PLANTIX): a citizen science project in cooperation with PEAT

Source: Anna Hampf, 2017
**Motivation:** There are few systematic research and monitoring programs on yield losses caused by plant diseases. Data is based on a limited number of site-specific tests or on a particular pathogen over one season.

**Solution:** Decentral data collection via Smartphone-App!

1. Select a crop!
2. Take a picture!
3. Get the result!
4. Control and preventive measures

Source: Anna Hampf, 2017
Why using a Smartphone-App?

- Decentral, large-scale data collection
- Simple collection of geo-referenced data that can be linked to climate and soil data afterwards
- Flexible, easy to use
- Smartphone penetration rate is increasing rapidly (Brazil: 26.3% in 2013 to 41% in 2015; Google; Pew Research Center)

Digital Image Processing

- Most diseases generate some kind of manifestation in the visible spectrum
- **Classification:** try to identify and label which pathology is affecting the plant
- Several classification methods (Thresholding, fuzzy classifier, feature-based rules, colour analysis) have been tested (Barbedo, 2013).

Main challenges

- Image background
- Image capture conditions
- Symptom segmentation
- Symptom variation
- Diseases with similar symptoms
- Multiple simultaneous disorder

*Source: Anna Hampf, 2017*
Results so far

- >500,000 received pictures
- ca. 120 automatic detectable plant diseases

Source: Anna Hampf, 2017
Sensor technologies and platforms to automatically detect and identify plant and P&D interactions at different scales

Fig. 2. Overview of current sensor technologies used for the automated detection and identification of host-plant interactions. These sensors can be implemented in precision agriculture applications and plant phenotyping on different scales from single cells to entire ecosystems. Depending on the scale, different platforms can be operated and consequently different plant parameters can be observed (Oerke et al. 2014, modified).
Changes of structural and chemical properties caused by pathogens alter optical patterns of leaves

A Leaf - Light Interaction

B Leaf - Pathogen Interaction

Colonization strategies of fungal pathogens

Reflectance [%/100] vs Wavelength [nm]

Healthy, Net blotch, Rust, Powdery mildew

Mahlein, 2016
### Examples of crop pathosystems and diseases assessed by optical sensors

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Crop</th>
<th>Disease / Pathogen</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RGB</strong></td>
<td>Cotton</td>
<td>Bacterial angular (<em>Xanthomonas campestris</em>)&lt;br&gt;Ascochyta blight (<em>Ascochyta goessypii</em>)</td>
<td>Camargo and Smith (2009)</td>
</tr>
<tr>
<td></td>
<td>Grapefruit</td>
<td>Citrus canker (<em>X. axonopodis</em>)</td>
<td>Bock et al. (2008)</td>
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<td></td>
<td>Tabaco</td>
<td>Anthracnose (<em>Colletotrichum destructivum</em>)</td>
<td>Wijekoon et al. (2008)</td>
</tr>
<tr>
<td></td>
<td>Apple</td>
<td>Apple scab (<em>Venturia inaequalis</em>)</td>
<td>Wijekoon et al. (2008)</td>
</tr>
<tr>
<td></td>
<td>Canadian goldentrod</td>
<td>Rust (<em>Coleosporium asterum</em>)</td>
<td>Wijekoon et al. (2008)</td>
</tr>
<tr>
<td><strong>Spectral sensors</strong></td>
<td>Barley</td>
<td>Net blotch (<em>Pyrenophora teres</em>),&lt;br&gt;Brown rust (<em>Puccinia hordei</em>),&lt;br&gt;Powdery mildew (<em>Blumeria graminis</em> <em>hordei</em>)</td>
<td>Kuska et al. (2015); Wahabzada et al. (2015a)</td>
</tr>
<tr>
<td></td>
<td>Wheat</td>
<td>Head blight (<em>Fusarium graminearum</em>),&lt;br&gt;Yellow rust (<em>Puccinia striiformis</em> f. sp. <em>tritici</em>)</td>
<td>Bauriegel et al. (2011); Bravo et al. (2003); Huang et al. (2007); Moshou et al. (2004)</td>
</tr>
<tr>
<td></td>
<td>Sugar beet</td>
<td>Cercospora leaf spot (<em>C. beticola</em>), Sugar beet rust (<em>U. betae</em>),&lt;br&gt;Powdery mildew (<em>Erysiphe betae</em>),&lt;br&gt;Root rot (<em>Rhizoctonia solani</em>),&lt;br&gt;Rhizomania (<em>Beet necrotic yellow vein virus</em>)</td>
<td>Bergsträsser et al. (2015); Hillnütter et al. (2011); Mahlein et al. (2010, 2012, 2013); Rumpf et al. (2010); Stoddem et al. (2003, 2005)</td>
</tr>
<tr>
<td></td>
<td>Tomato</td>
<td>Late blight (<em>Phytophthora infestans</em>)</td>
<td>Wang et al. (2008)</td>
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<tr>
<td></td>
<td>Apple</td>
<td>Apple scab (<em>V. inaequalis</em>)</td>
<td>Delalieux et al. (2007)</td>
</tr>
<tr>
<td></td>
<td>Tulip</td>
<td><em>Tulip breaking virus</em> (<em>TBV</em>)</td>
<td>Polder et al. (2014)</td>
</tr>
<tr>
<td></td>
<td>Sugar cane</td>
<td>Orange rust (<em>Puccinia kuehnii</em>)</td>
<td>Apan et al. (2004)</td>
</tr>
<tr>
<td><strong>Thermal sensors</strong></td>
<td>Sugar beet</td>
<td>Cercospora leaf spot (<em>C. beticola</em>)</td>
<td>Chaerle et al. (2004)</td>
</tr>
<tr>
<td></td>
<td>Cucumber</td>
<td>Downy mildew (<em>Pseudoperonospora cubensis</em>), Powdery mildew (<em>Podosphaera xanthii</em>)</td>
<td>Berdugo et al. (2014); Oerke et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>Apple</td>
<td>Apple scab (<em>V. inaequalis</em>)</td>
<td>Oerke et al. (2011)</td>
</tr>
<tr>
<td></td>
<td>Rosa</td>
<td>Downy mildew (<em>Peronospora sparsa</em>)</td>
<td>Gomez (2014)</td>
</tr>
<tr>
<td><strong>Fluorescence imaging</strong></td>
<td>Wheat</td>
<td>Leaf rust (<em>Puccinia triticina</em>),&lt;br&gt;Powdery mildew (<em>Blumeria graminis</em> f. sp. <em>tritici</em>)</td>
<td>Bürling et al. (2011)</td>
</tr>
<tr>
<td></td>
<td>Sugar beet</td>
<td>Cercospora leaf spot (<em>C. beticola</em>)</td>
<td>Chaerle et al. (2004, 2007); Konanz et al. (2014)</td>
</tr>
<tr>
<td></td>
<td>Bean</td>
<td>Common Bacterial Blight (<em>Xanthomonas fuscans</em> subsp. <em>fuscans</em>)</td>
<td>Rousseau et al. (2013)</td>
</tr>
<tr>
<td></td>
<td>Lettuce</td>
<td>Downy mildew (<em>Bremia lactucae</em>)</td>
<td>Bauriegel et al. (2014); Brabandt et al. (2014)</td>
</tr>
</tbody>
</table>

Mahlein, 2016
What would be desirable for assessing production risks

Models for important P & D linked to crop models to have a system, which should be responsive to:

- Climatic conditions,
- Crop and pest management options including:
  - crop rotations
  - residue management or tillage
  - water and nutrient management
  - pesticide / bio-protector applications

Providing information on:

- Crop losses
- Adapted best pest management practices,
- Environmental impacts, e.g. on water resources, biodiversity, ...
- Economic impacts for production (cost-benefit)
Thank you for your attention

All models are wrong, some models are useful  
G.E.P. Box, 1979