The role of process-based modelling in agro-ecosystem research

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Outline

- The scientific approach and models
- Why modelling?
- Model complexity and model uncertainty
- Examples of model applications
  - Decision support on field scale
  - Adressing spatial variability
  - Evaluation of management options
  - Assessing long term effects
  - Considering biotic stress

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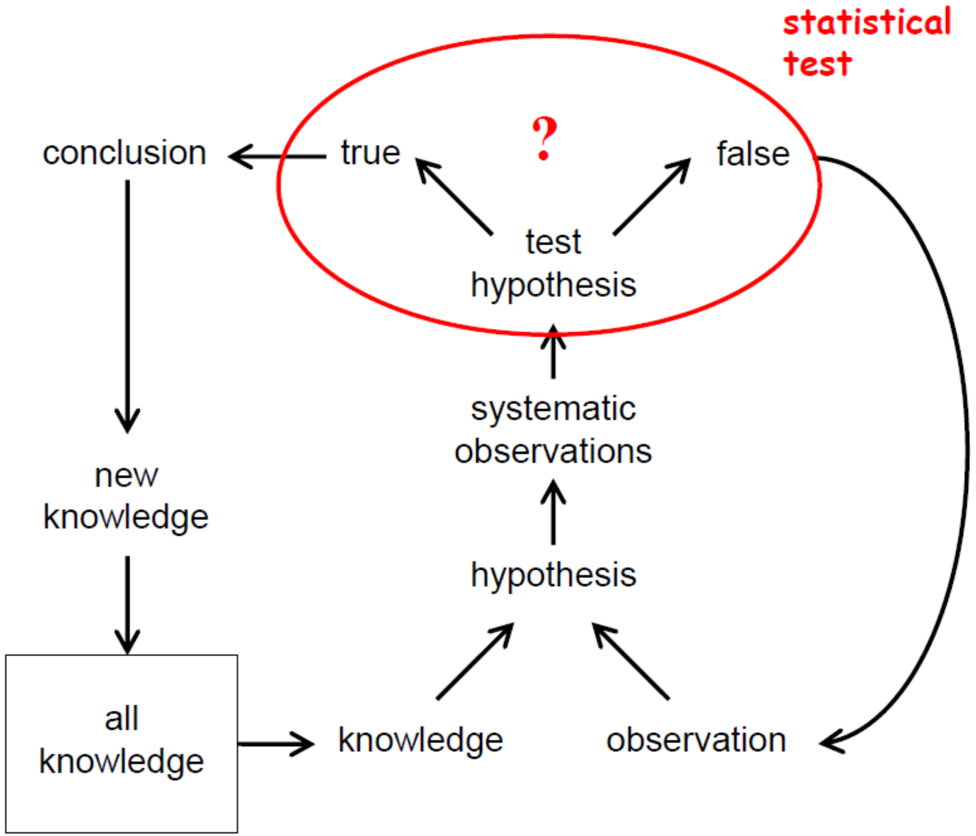
The scientific method



What is a model?

In general:

- An idealised, simplified or down-sized representation of something ...
- ... the purpose is to describe, explain or depict the thing the model represents

A simplified description of truth

Claude Monet
(1840-1926)

Impressionism

Claude Monet‘s garden at Giverny, France

What is a model in science?

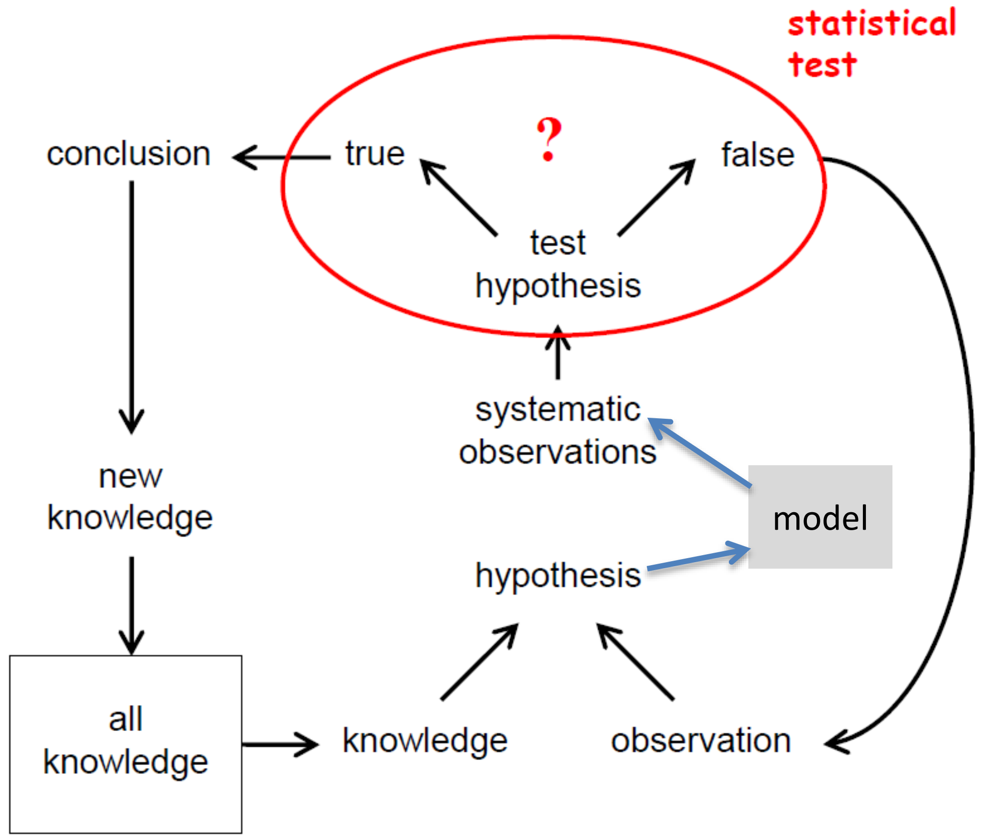
In science:

- An idealised or simplified conceptual or formal representation of a phenomenon or item of interest, usually from the real world
- ... the purpose is to describe, explain or study the real-world phenomenon the model represents ...
- ... enabling conclusions to be drawn about its properties or behaviour

Part of the scientific method:

- A model may be thought of as a formalised or explicit hypothesis about the real-world phenomenon under investigation
- May be falsified by comparing its predictions to observational data. False model = rejected hypothesis

The model to test hypothesis



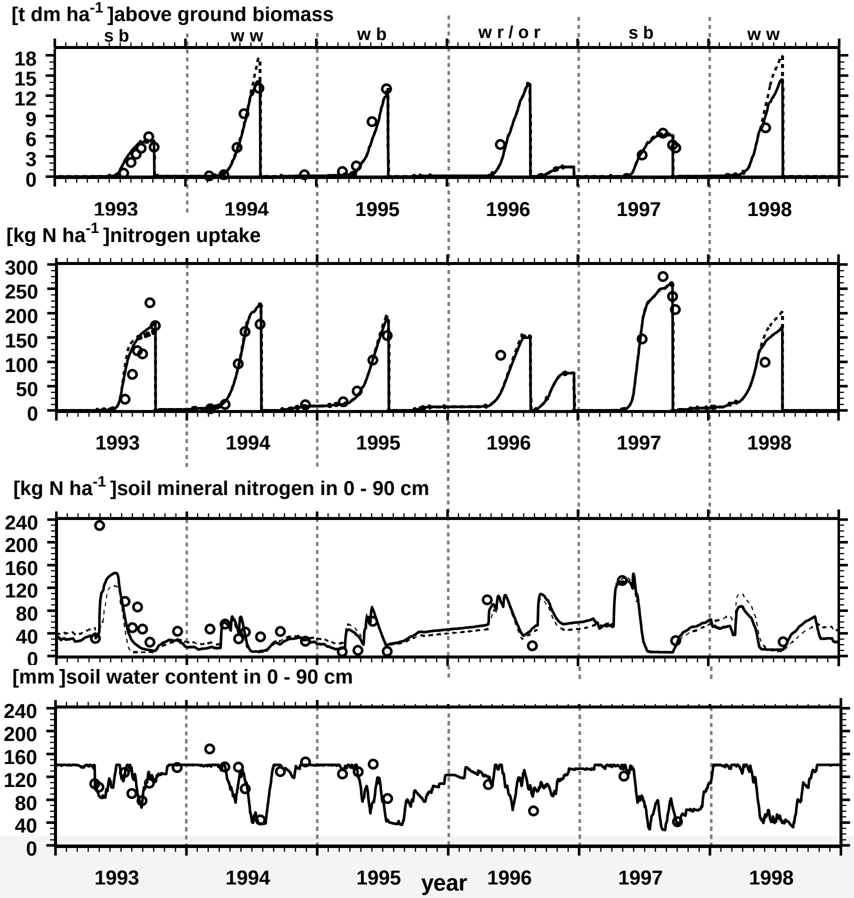
Why are we modelling?

- Models can be used to test hypotheses using observed data for a better understanding.
- They may also indicate which variables should be observed to confirm the hypothesis (experimental design).
- Experimental data are covering only few combinations of possible climate, site, crop and management combinations.
- Processes are interacting, usually non-linear and response is site specific and therefore experimental data seem often contradictory.
- Not all fluxes can be observed easily or with sufficient accuracy
- Responses can be very slowly and would require a long term monitoring to be detectable
- Climate change can create situations which are beyond our experience
- As long as we achieve a sufficient performance of our model to explain observed phenomena under multiple conditions, we assume that we can use the model to extrapolate to other situations even if they are beyond our experience.
- This allows the assessment of what-if scenarios

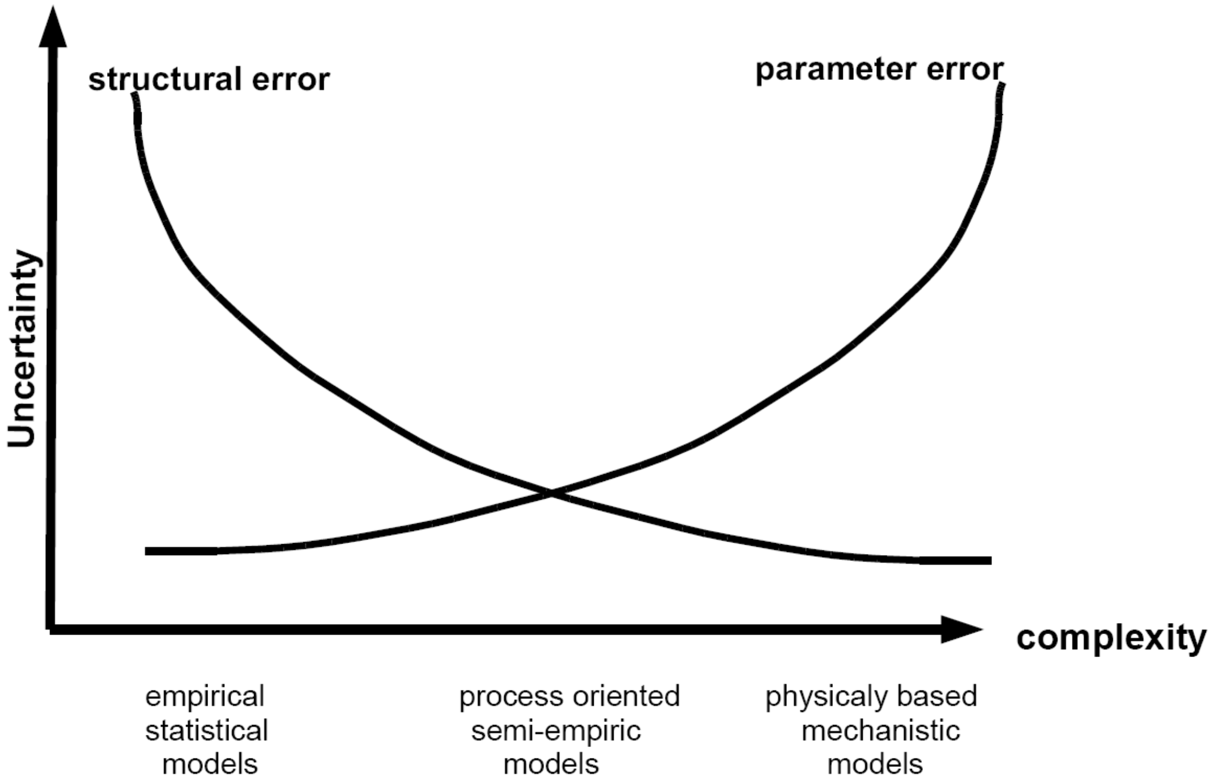
But, no data -> no model

- Models can complement or extrapolate data, but cannot be used without a reliable data base.
- Models should be validated/evaluated on independent data which are not used for calibration.
- Models should be evaluated applying them to multiple combinations of site and management conditions to find limitations of assumptions or to falsify hypotheses.
- Since processes are interacting, it is necessary to evaluate not only a single output variable against observed data, but multiple inter-related variables to ensure that the model gives the right output on the right reason.
- However, validation of models has its limitations since ecosystems are open systems and not all inputs across the system boundaries can be detected.

Validation of complex models requires consistent data sets of different observed state variables



Model complexity and uncertainty

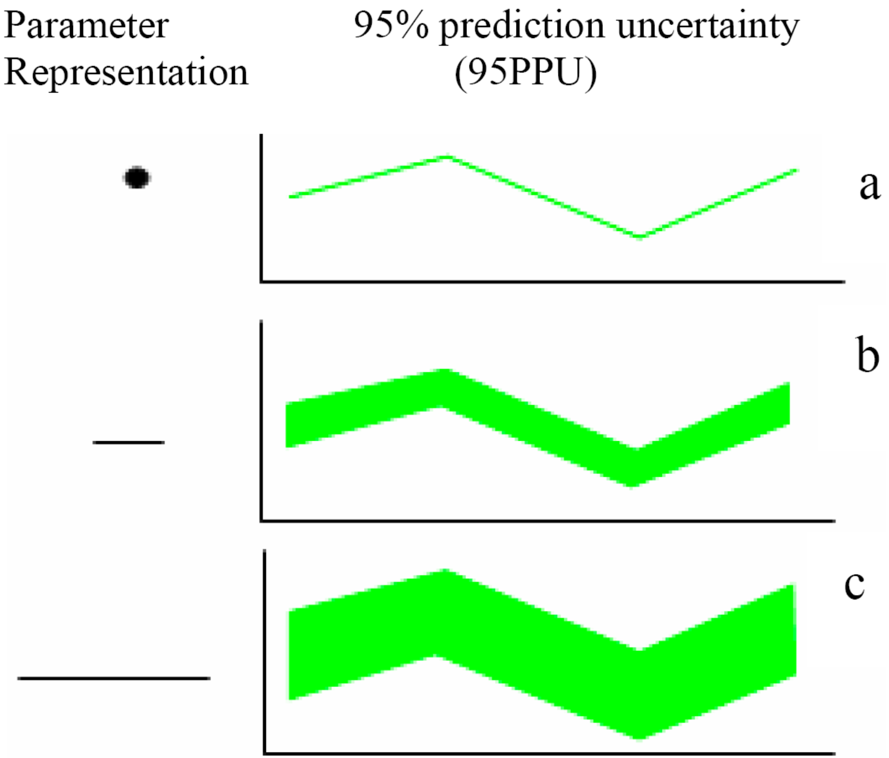


adapted from Grunewald

Relationship between parameter uncertainty and prediction uncertainty

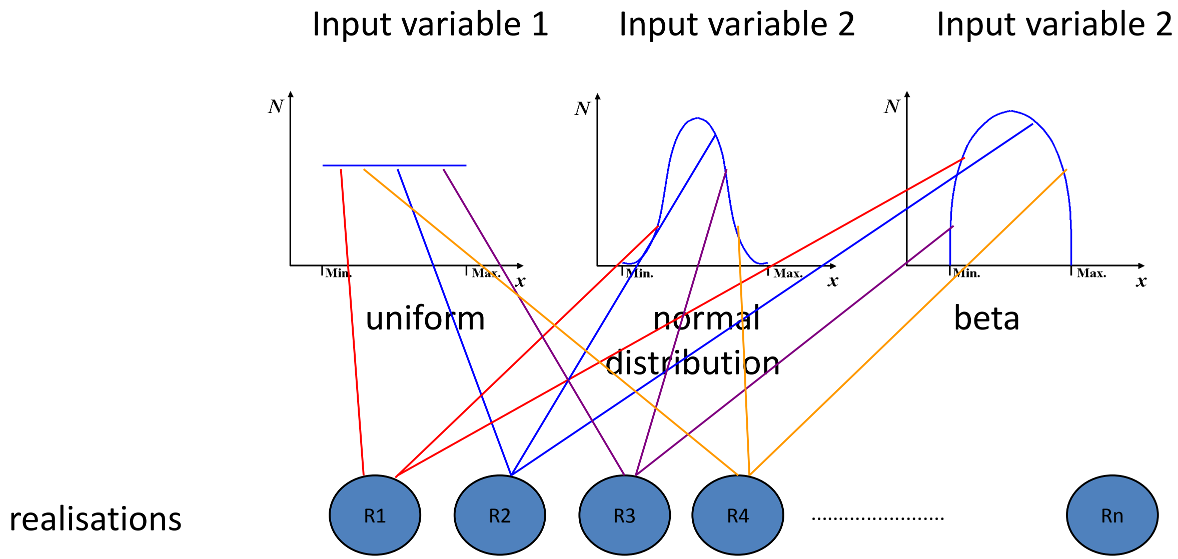
Deterministic model

Stochastic model



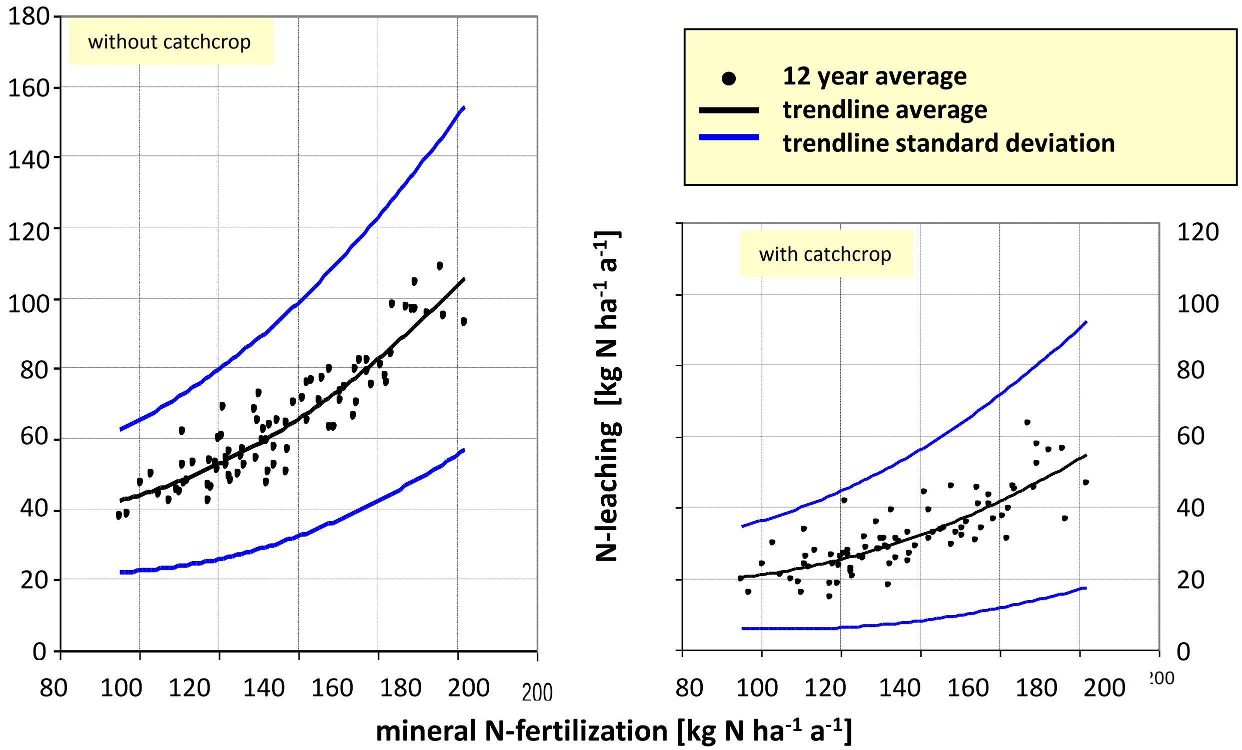
Abbaspour, 2005

Stochastic modelling uses stochastic distributions of input values



Monte Carlo simulation generates a large number of input combinations which leads to a large number of different output values (stochastic distribution)
Introduction of sampling procedures e.g. Latin hypercube (Christiaens und Feyen,2002) reduces the number of simulation runs

Uncertainty of simulated nitrate leaching for barley depending on fertilization sandy „Plaggenesch“ (deep accumulated humus layer) over loam



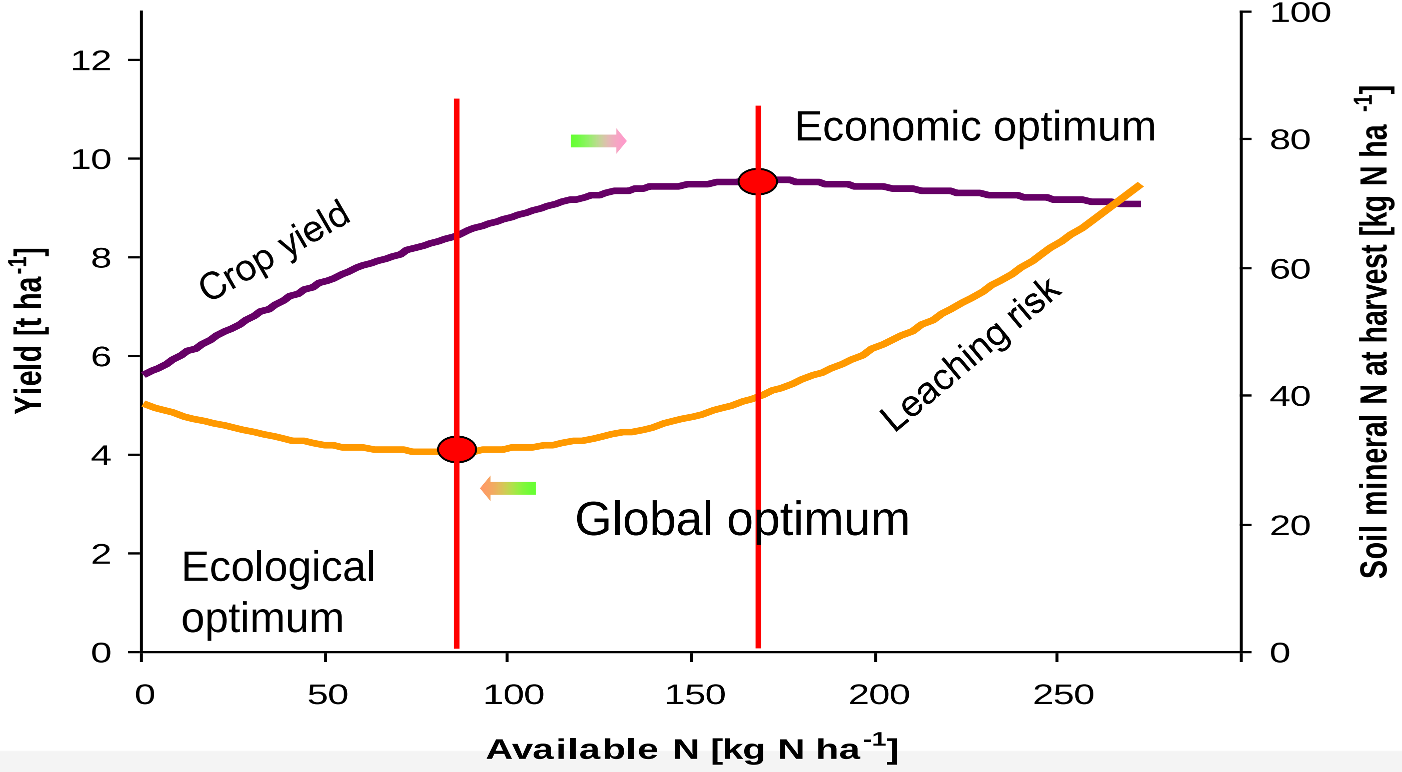
Considered uncertainties:

Field capacity, available water, Corg, C:N, groundwater level, sowing and harvest date, fertilization dates and amounts

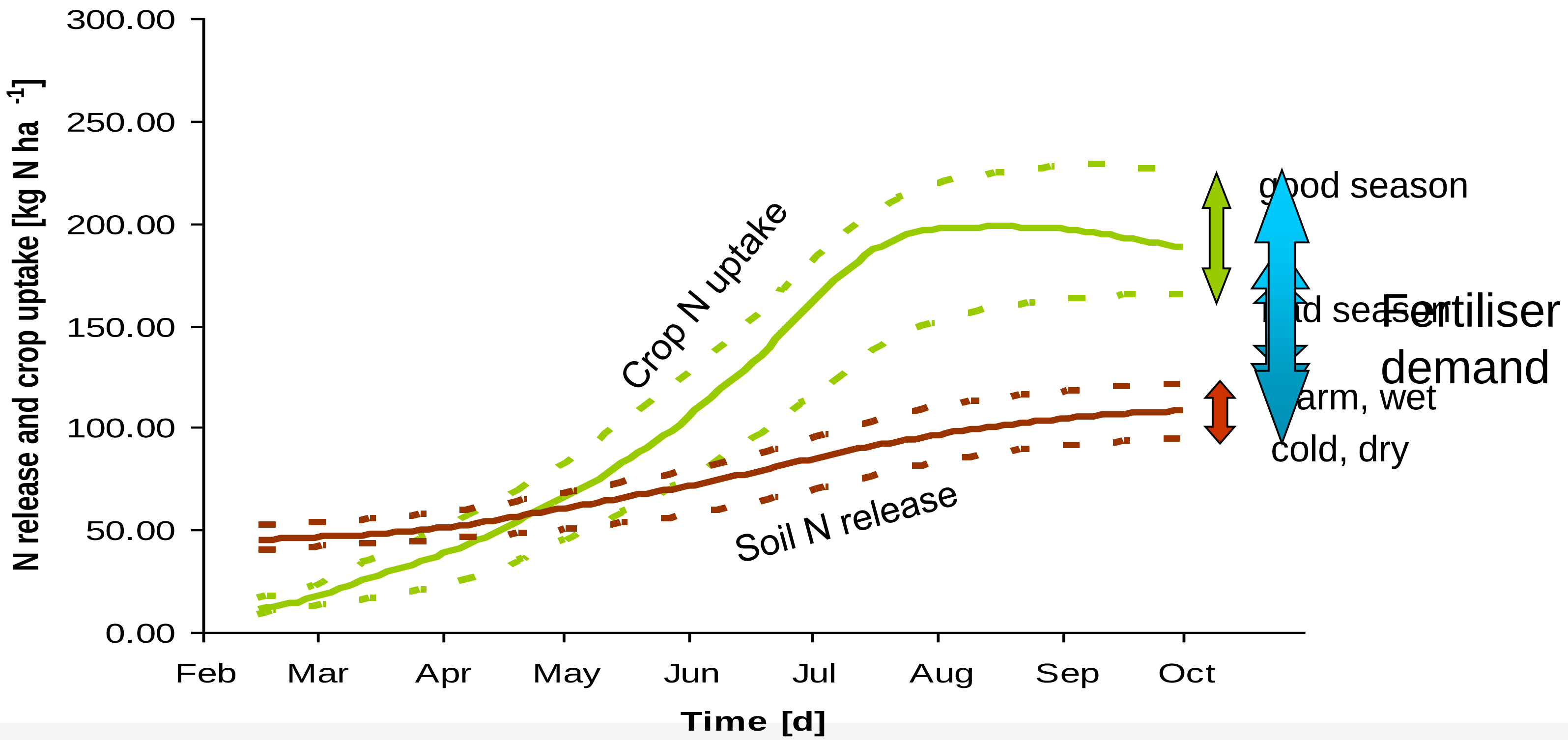
Method: Latin Hypercube Simulation, 80 combinations for 2 fertilizer applications

Source: Grimm, 2006

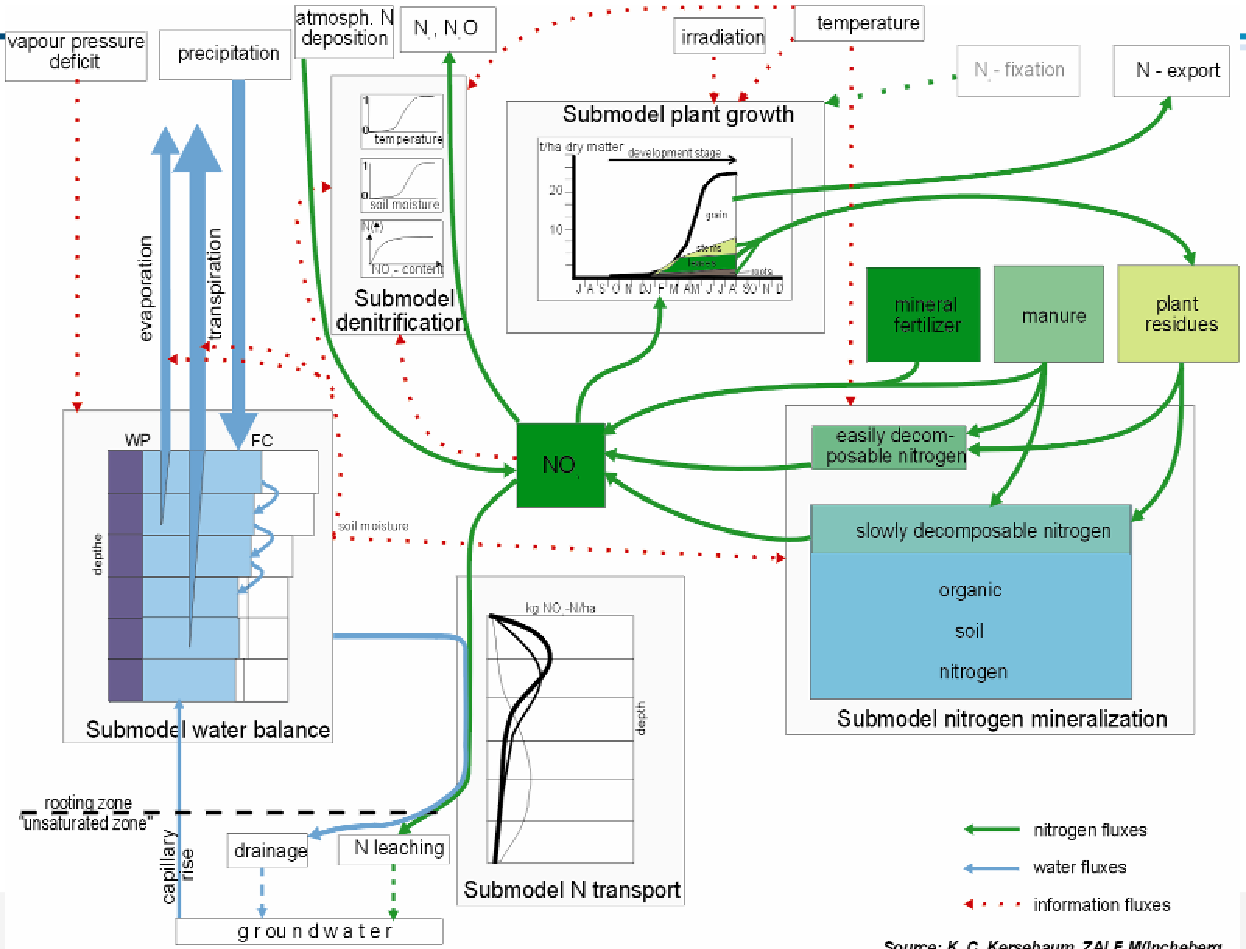
What's the optimum fertiliser rate?



Callenge: Nitrogen fertiliser demand varies from year to year



Scheme of the agro-ecosystem model HERMES



Source: K. C. Kersebaum, ZALF Müncheberg

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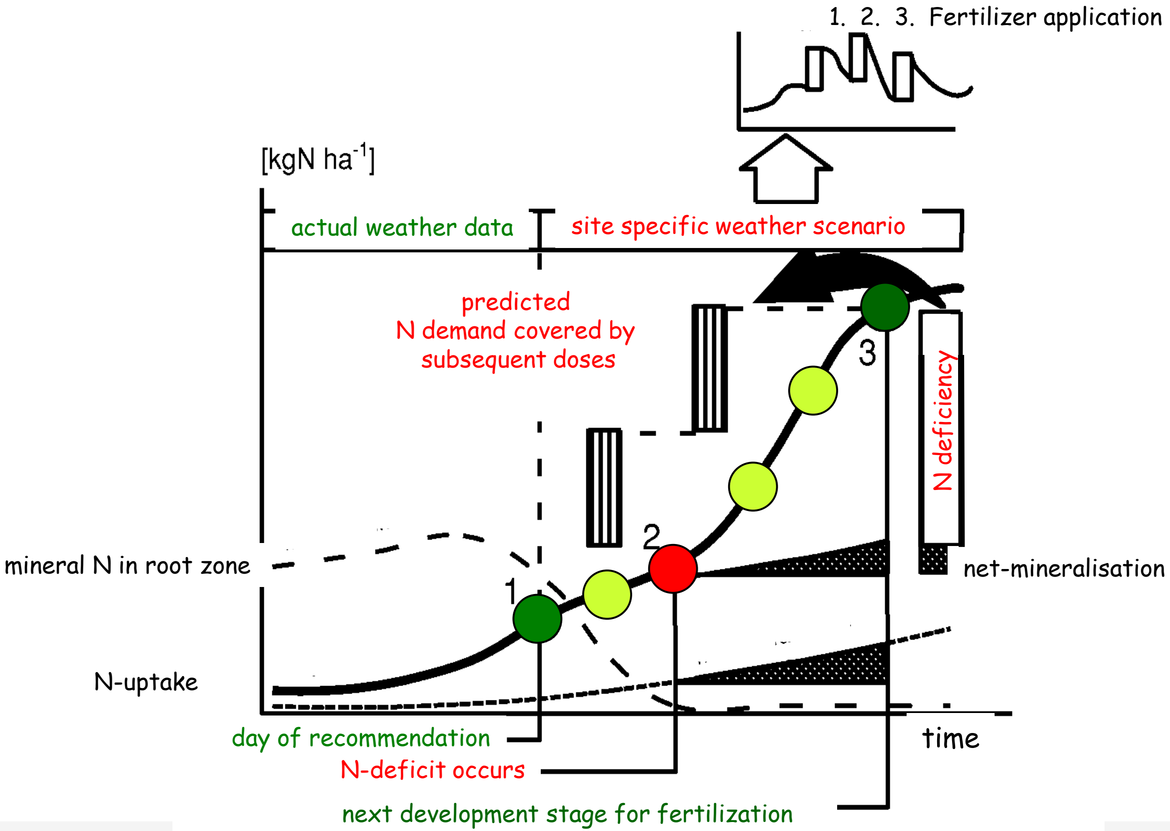
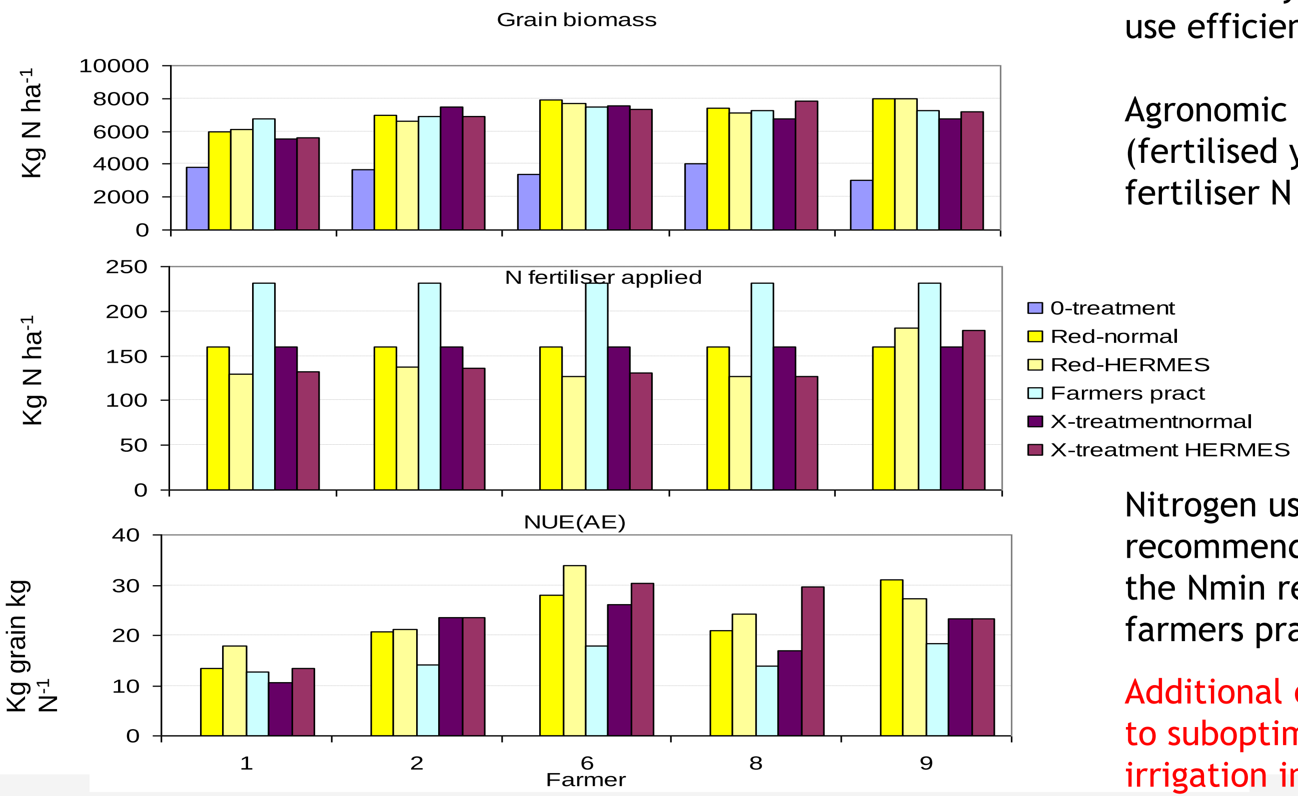
Scheme of model based fertilizer recommendations



Kersebaum & Beblik, 2001

Model based fertiliser recommendations compared to other treatments for different Chinese farmers



Measured yields, applied nitrogen and nitrogen use efficiency for winter wheat 2010/11

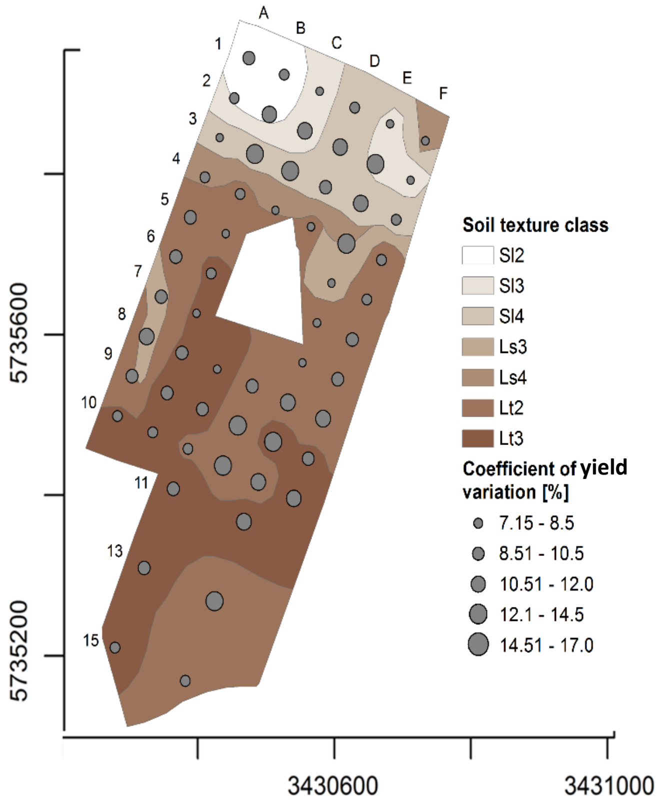
Agronomic efficiency of applied N (NUE_{AE}) = (fertilised yield – unfertilised yield) / applied fertiliser N

Nitrogen use efficiency of the model recommendation is in most cases higher than of the Nmin recommendation method (normal) and farmers practice

Additional outcome: Low NUE was often related to suboptimal flood irrigation. Optimizing irrigation improves WUE and NUE significantly

Adressing spatial variability within fields (precison agriculture)

20 ha field at Beckum, NRW

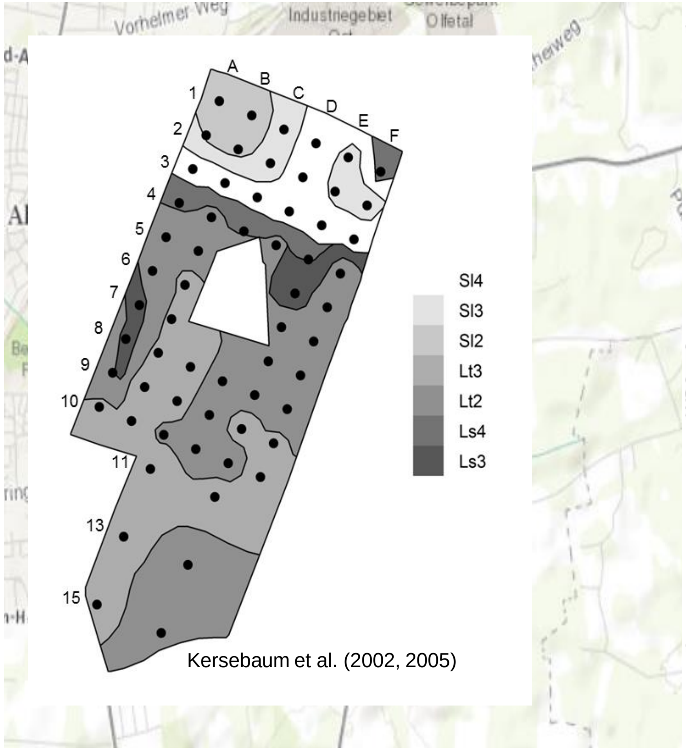


Range of clay, silt and sand content per soil texture class (Ad-hoc AG Boden 2005, German Soil Taxonomy)

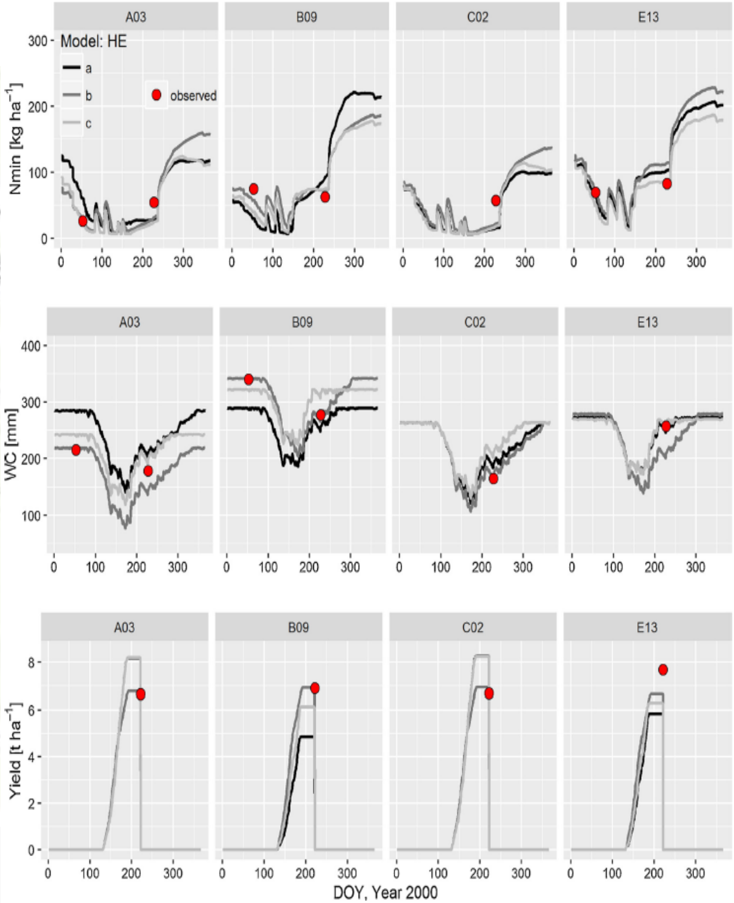
Soil texture class	Clay [%]	Silt [%]	Sand [%]
Sl2	5 - 8	10 - 25	67 - 85
Sl3	8 - 12	10 - 40	48 - 82
Sl4	12 - 17	10 - 40	43 - 78
Ls3	17 - 25	30 -40	35 - 53
Ls4	17 - 25	15 - 30	45 - 68
Lt2	25 - 35	30 -50	15 -45
Lt3	35 - 45	30 - 50	5 - 35

- crop rotation: WW-WW-TR (2000 to 2002)
- weather data from local weather station
- data for validation (<u>soil nitrogen</u>, <u>soil water</u>, <u>yields</u>)

Examples of model outputs (HERMES) and data



Kersebaum et al. (2002, 2005)



a = low calibration
b = medium calibr.
c = full calibration

Wallor et al. 2018

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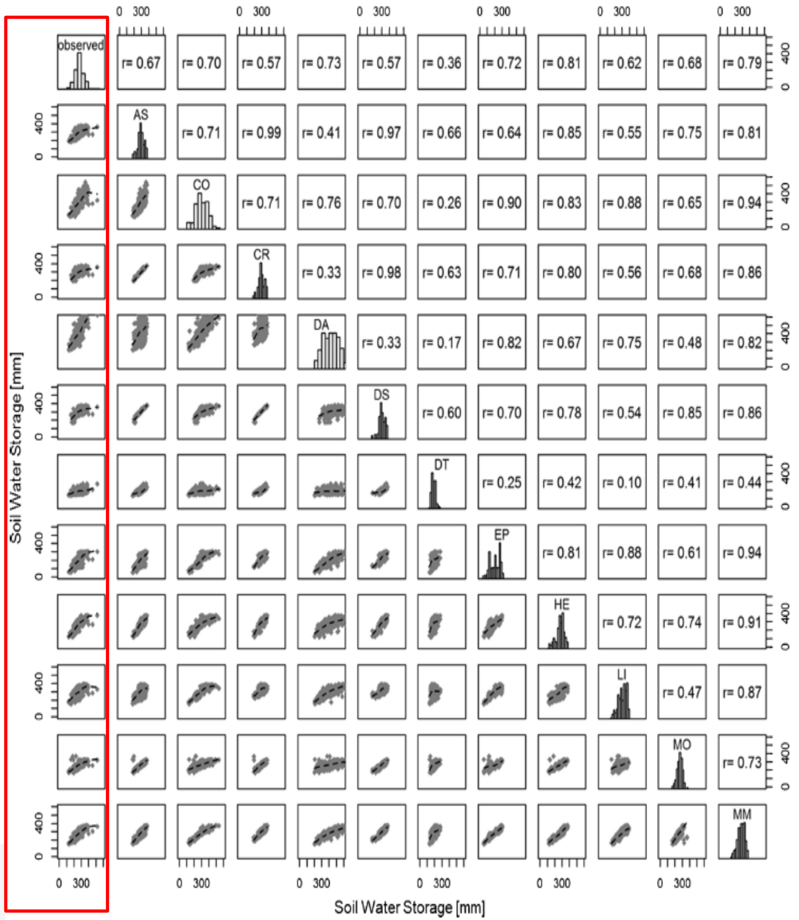
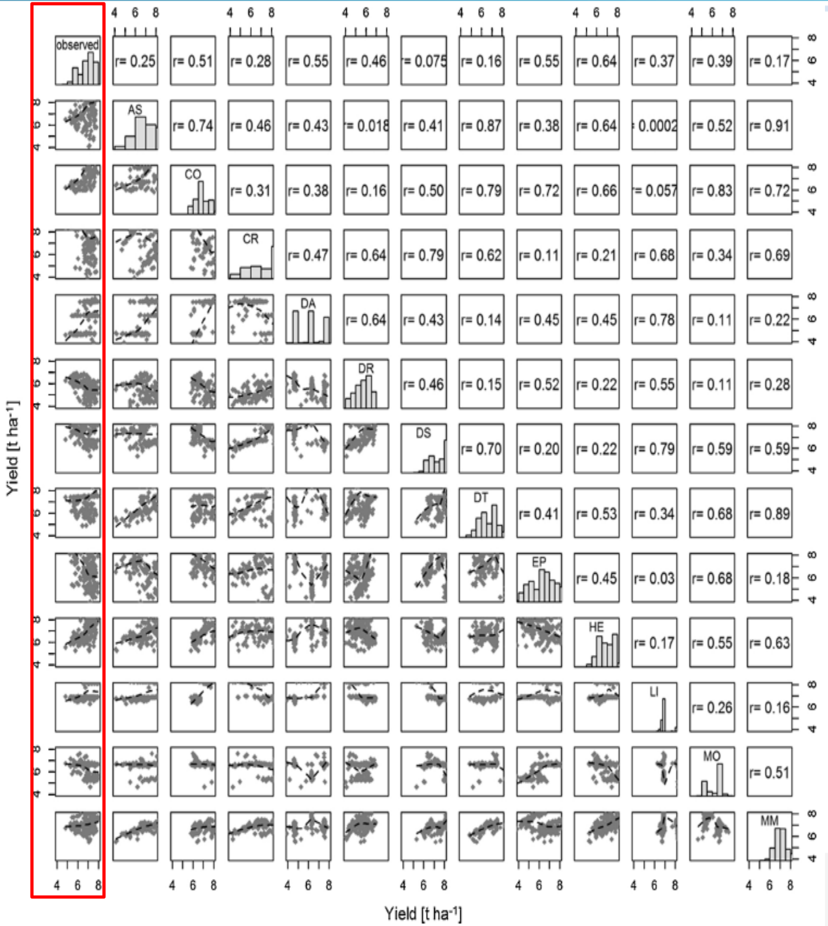
Results of a model ensemble on soil water and crop yields





Wallor et al. 2018

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Testing model consistency among output variables

Models' consistency:

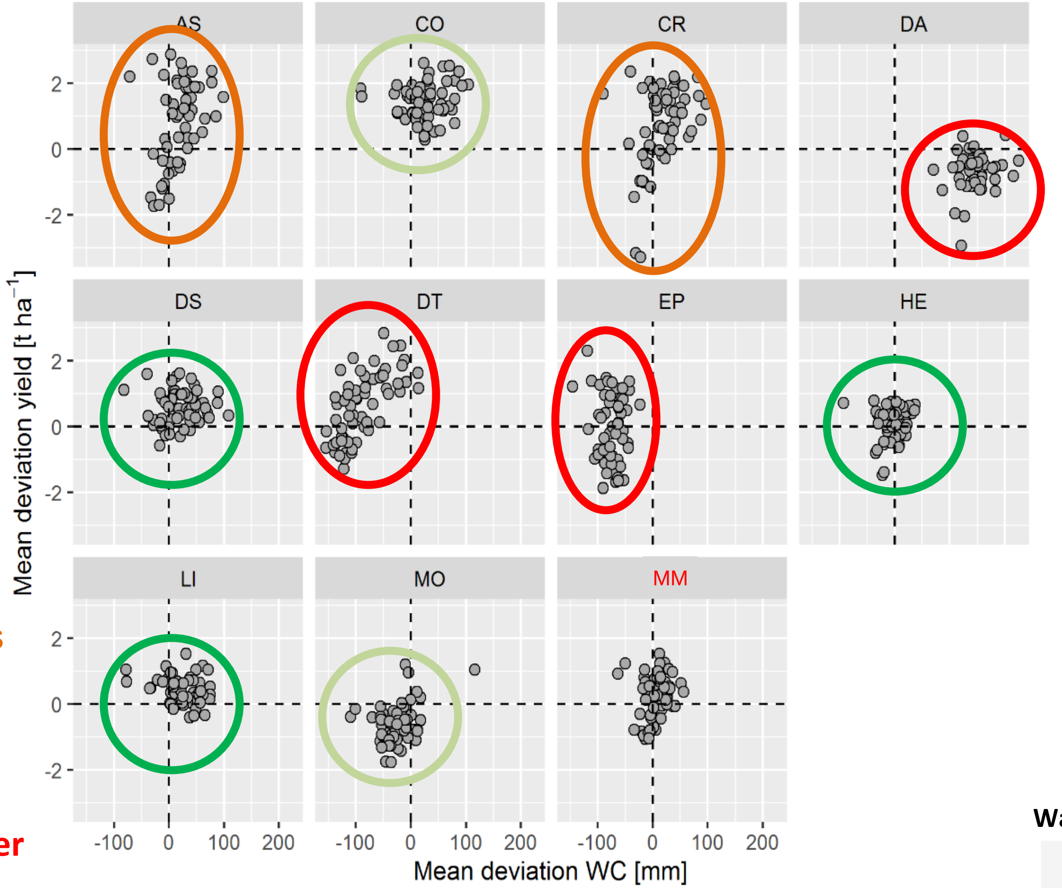
High consistency, sufficiently well calibrated:

Points are close to the intersection of the zero lines

Consistent, but insufficiently calibrated: Deviations are in the same direction

Too sensitive showing steep responses caused by small deviations

Not consistent regarding the response to the variable or responsive to another variable



Wallor et al. 2018

Increasing spatial resolution using soil sensor information and point based texture

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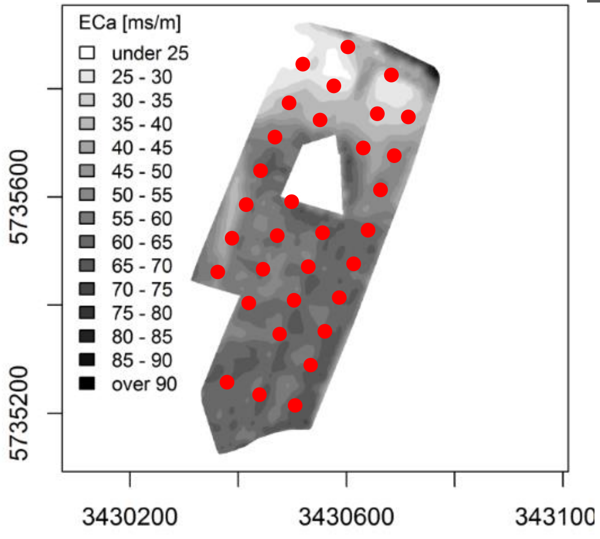
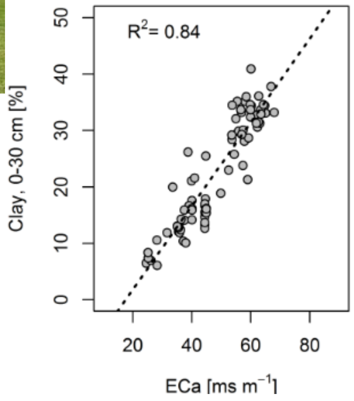
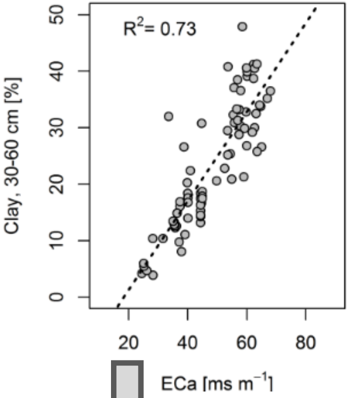
Continuous detection complements manual point sampling



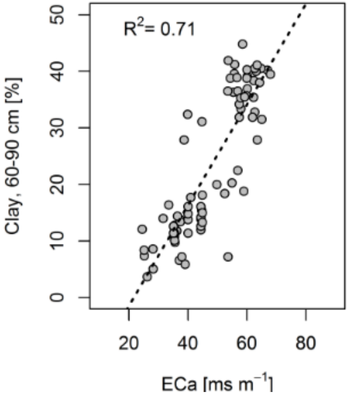
0-30cm



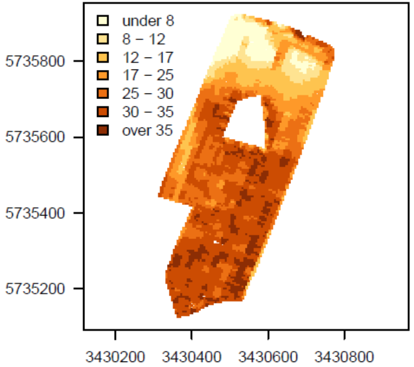
30-60cm



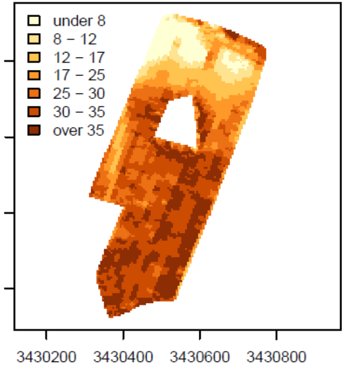
60-90cm



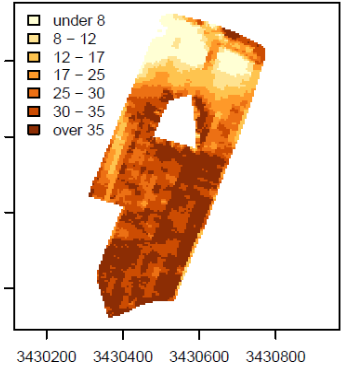
0-30cm



30-60cm



60-90cm



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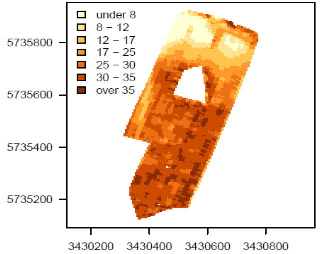
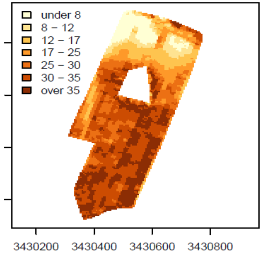
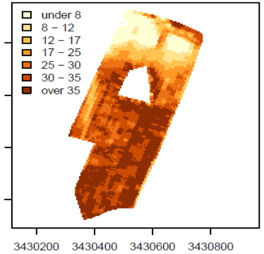
Application of high resolution soil map for spatio-temporal modelling



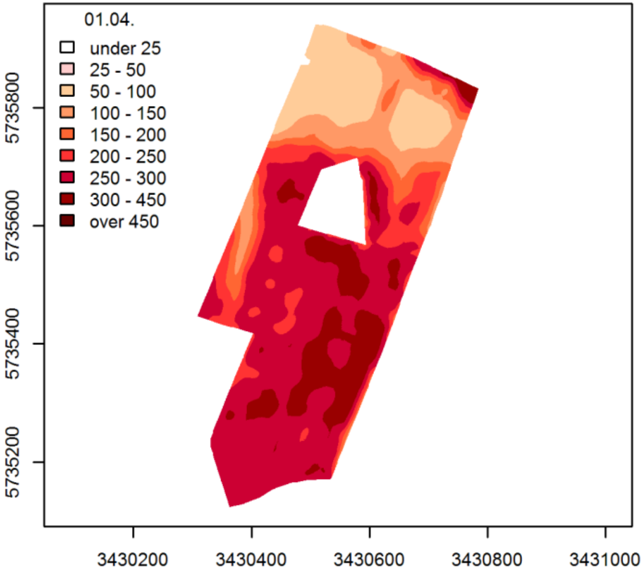


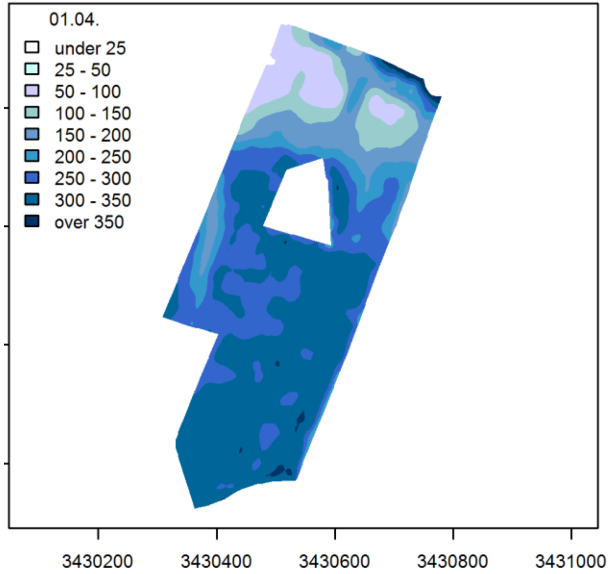


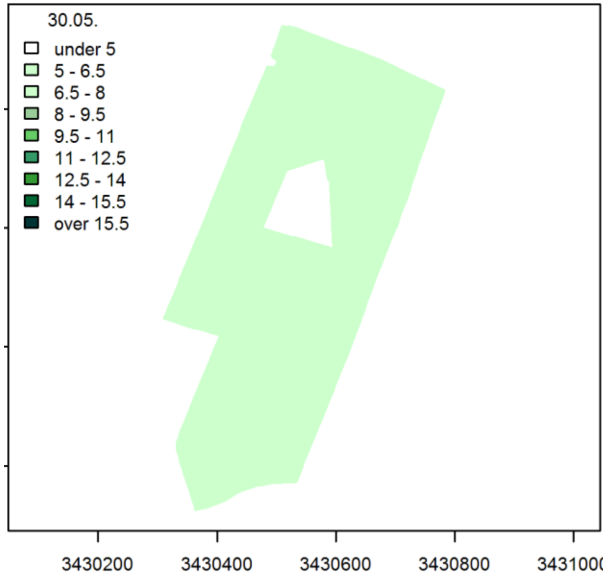
Nmin in 0-90 cm [kg N / ha]

Soil water content in 0-90 cm [mm]

Above ground crop biomass (t / ha)







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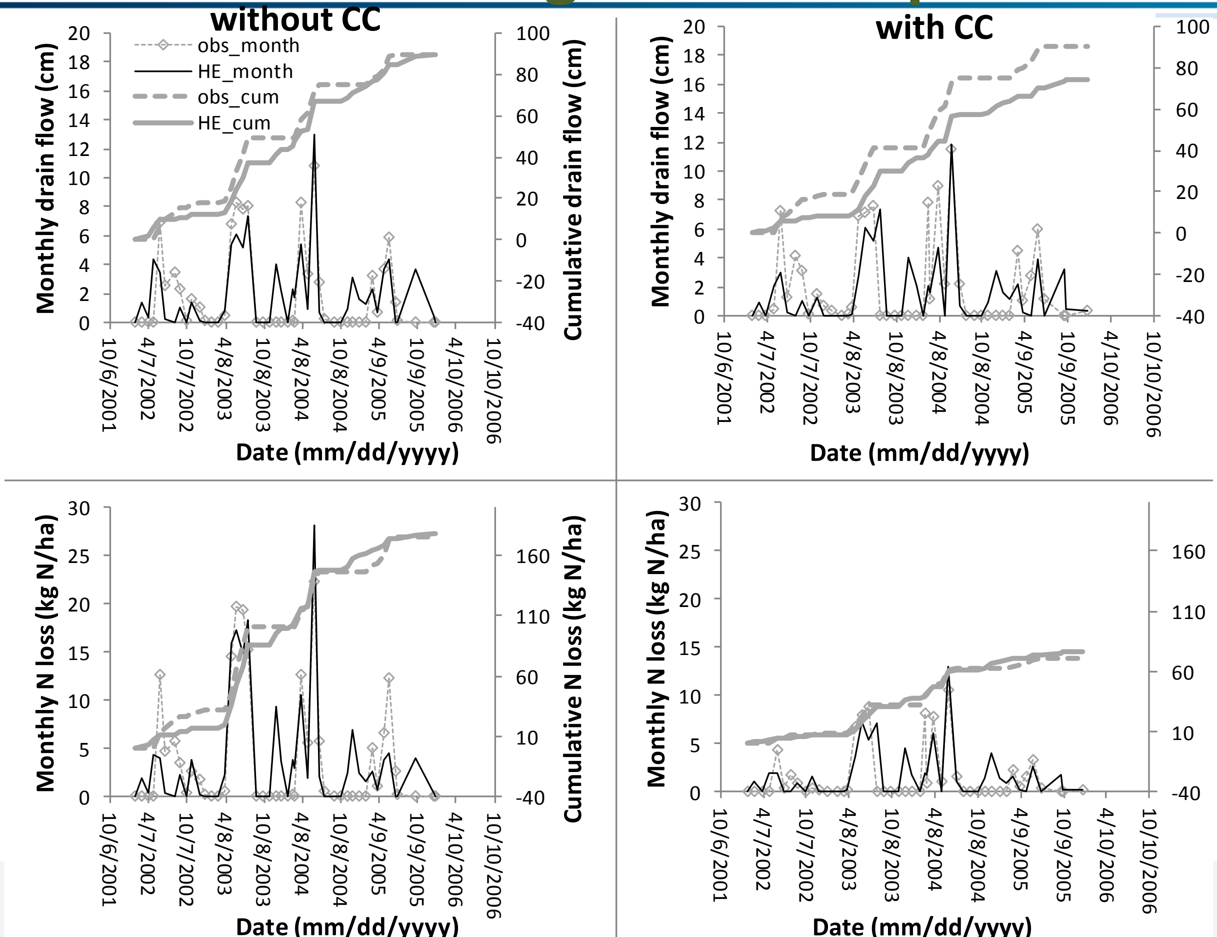
Evaluating rotation options for water protection

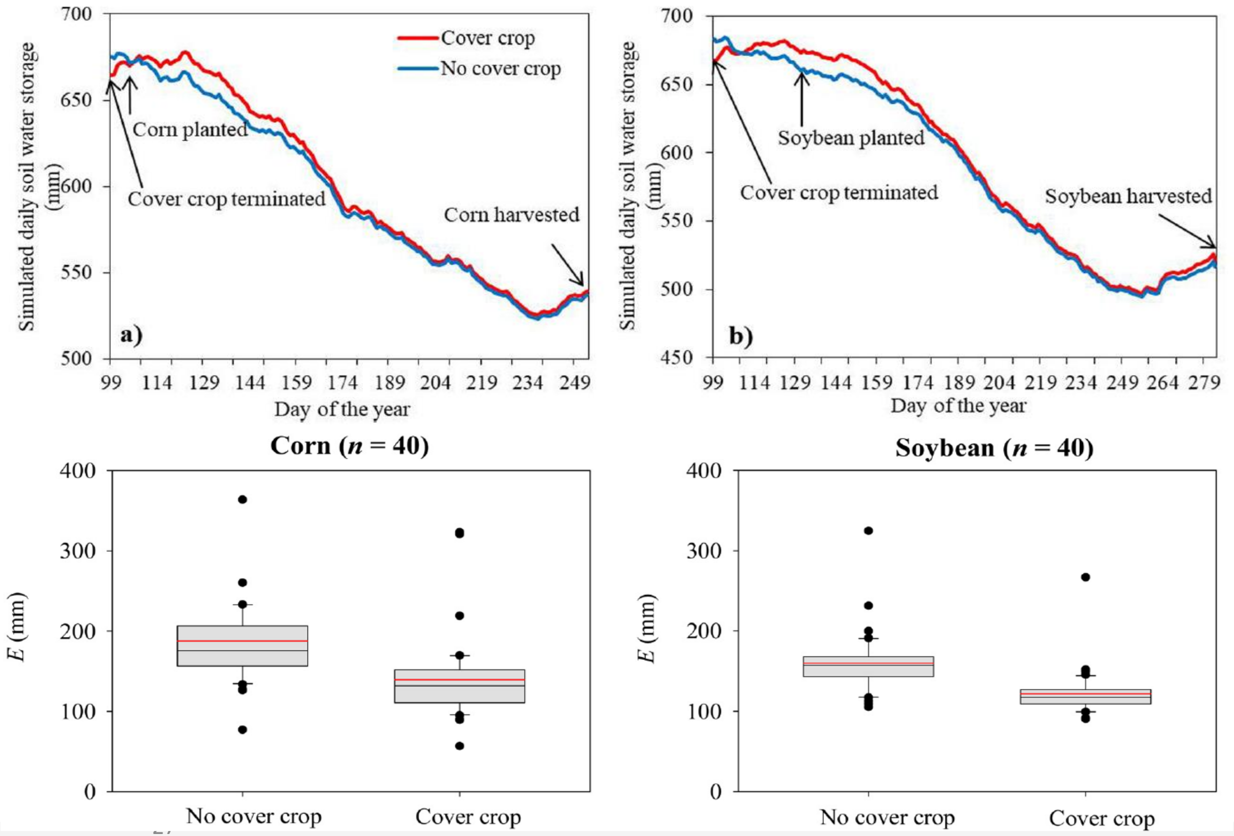


Effects of w.rye cover crop on tile drain water and N flow in a corn - soybean rotation at Ames, Iowa

CC: with catch crop
NCC: without CC

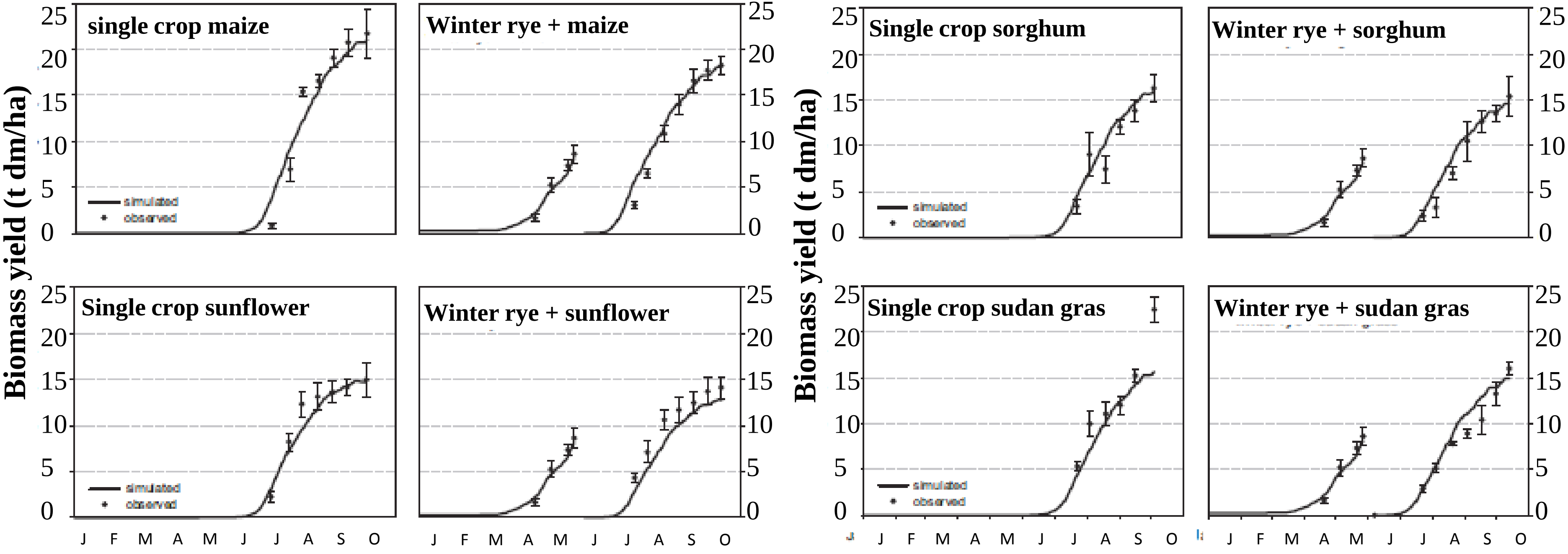
Malone et al., Agric. Water Man. 2017

Mulching cover crop residues may compensate it´s higher water use



Simulated (RZWQM2) soil water storage (1.8 m) under a) maize and b) soybean after winter fallow or rye cover crop, and related soil evaporation E under c) maize and d) soybean (40 years for each crop during 1938-2017) **(Yang et al. 2019)**

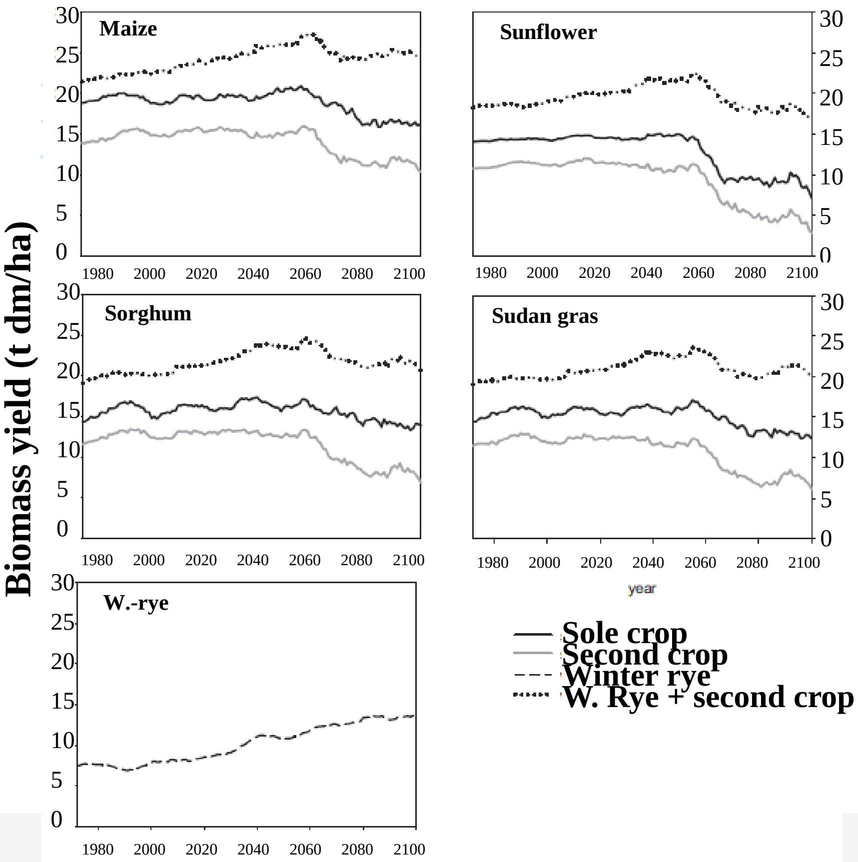
Testing the feasibility of new crops and double cropping under present climatic conditions in Germany

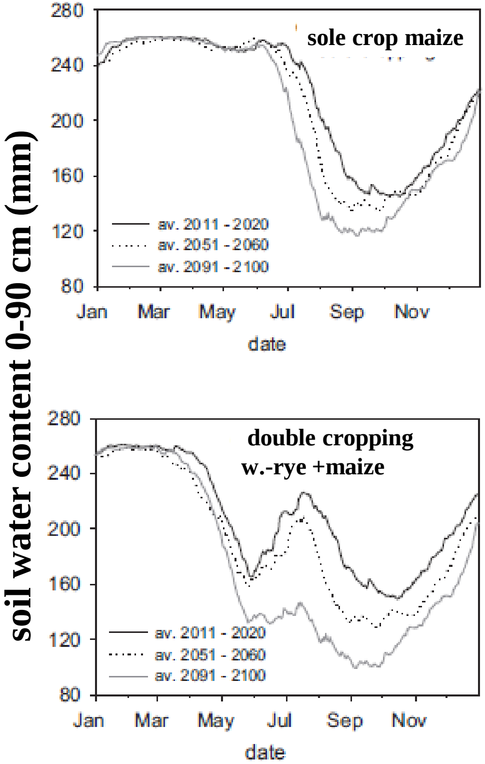


Site Witzenhausen/Germany
Year 2010
Simulation HERMES

Graß et al. 2015, Eur. J. Agron.

Future water availability and competition has to be taken into account under Climate Change





Graß et al. 2015, Eur. J. Agron.

CO_2-effects have to be considered in climate change impact studies

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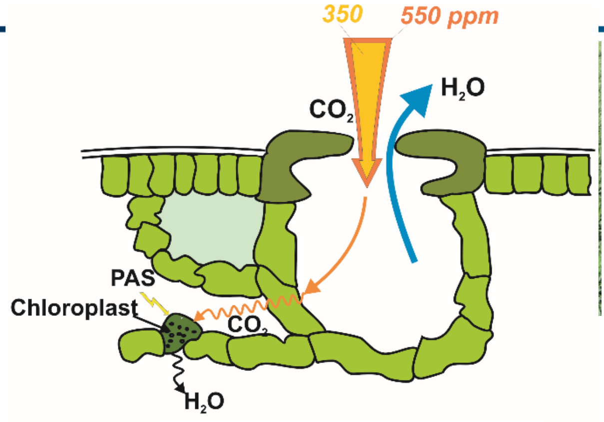
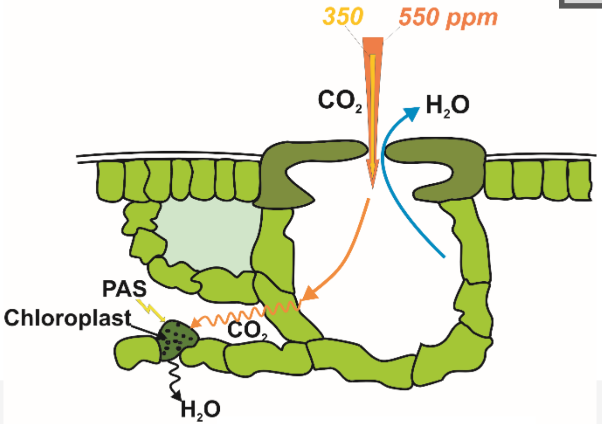
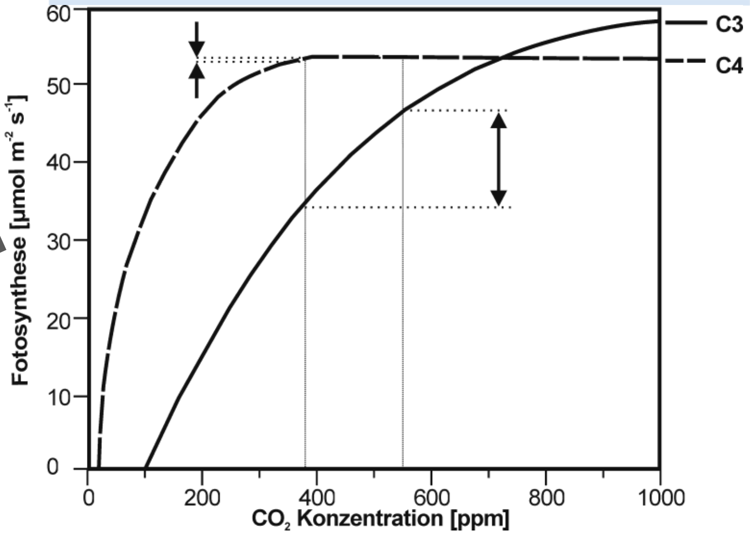


sufficient water



under water stress

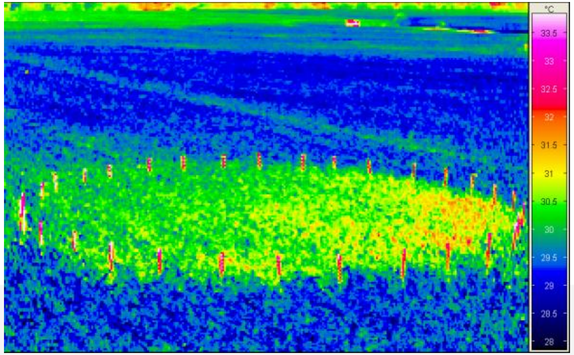


Higher photosynthesis (C3)

Reduced transpiration

-> higher water use efficiency

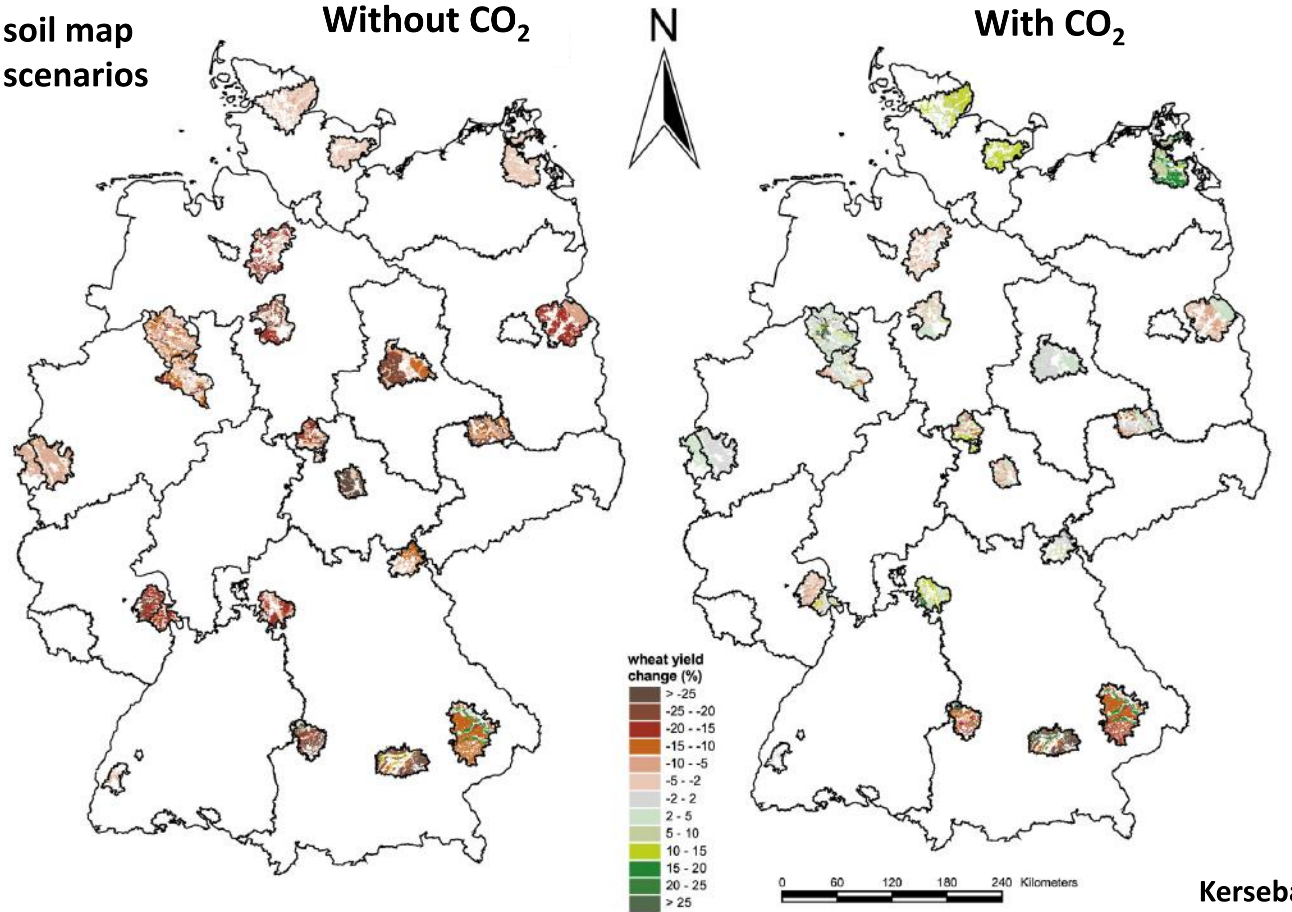
-> higher canopy temperature



Yield?

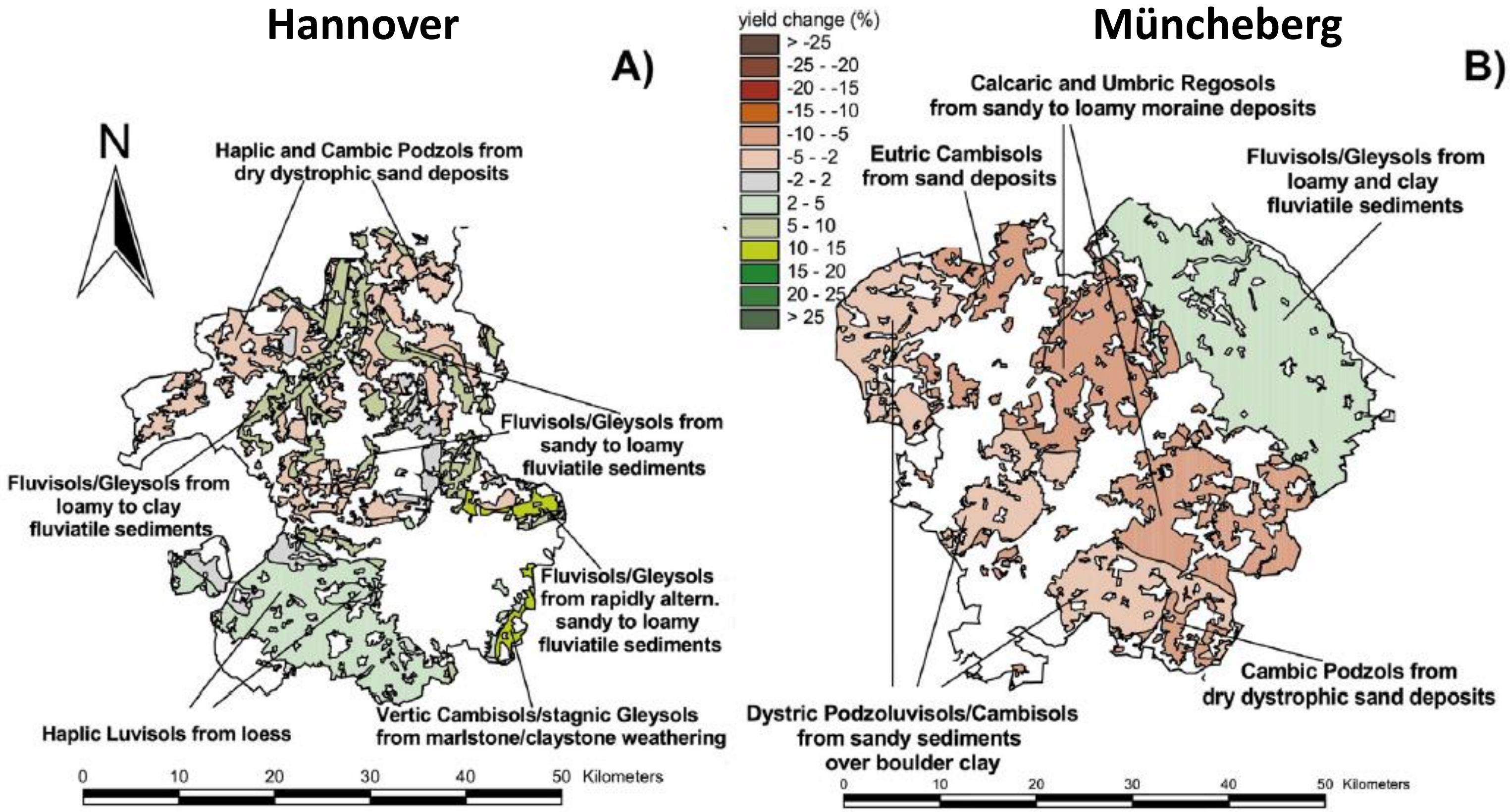
Extrapolation to other sites to assess CC impact

Based on 1:1.000.000 soil map
Local weather station scenarios



Kersebaum & Nendel 2014

Climate change effects are site specific!



Kersebaum & Nendel 2014

Relevance of processes may change with site

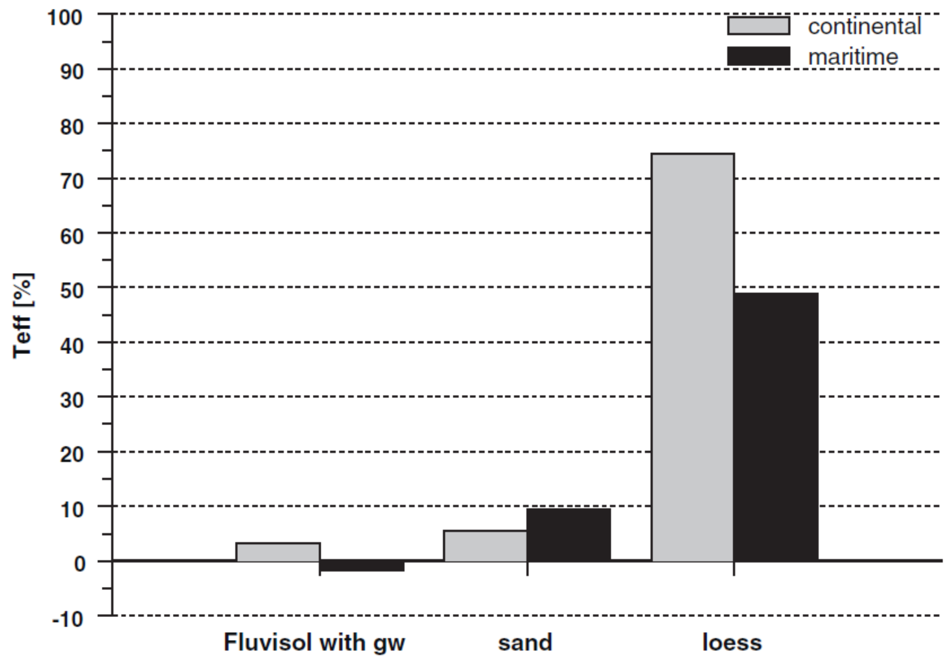


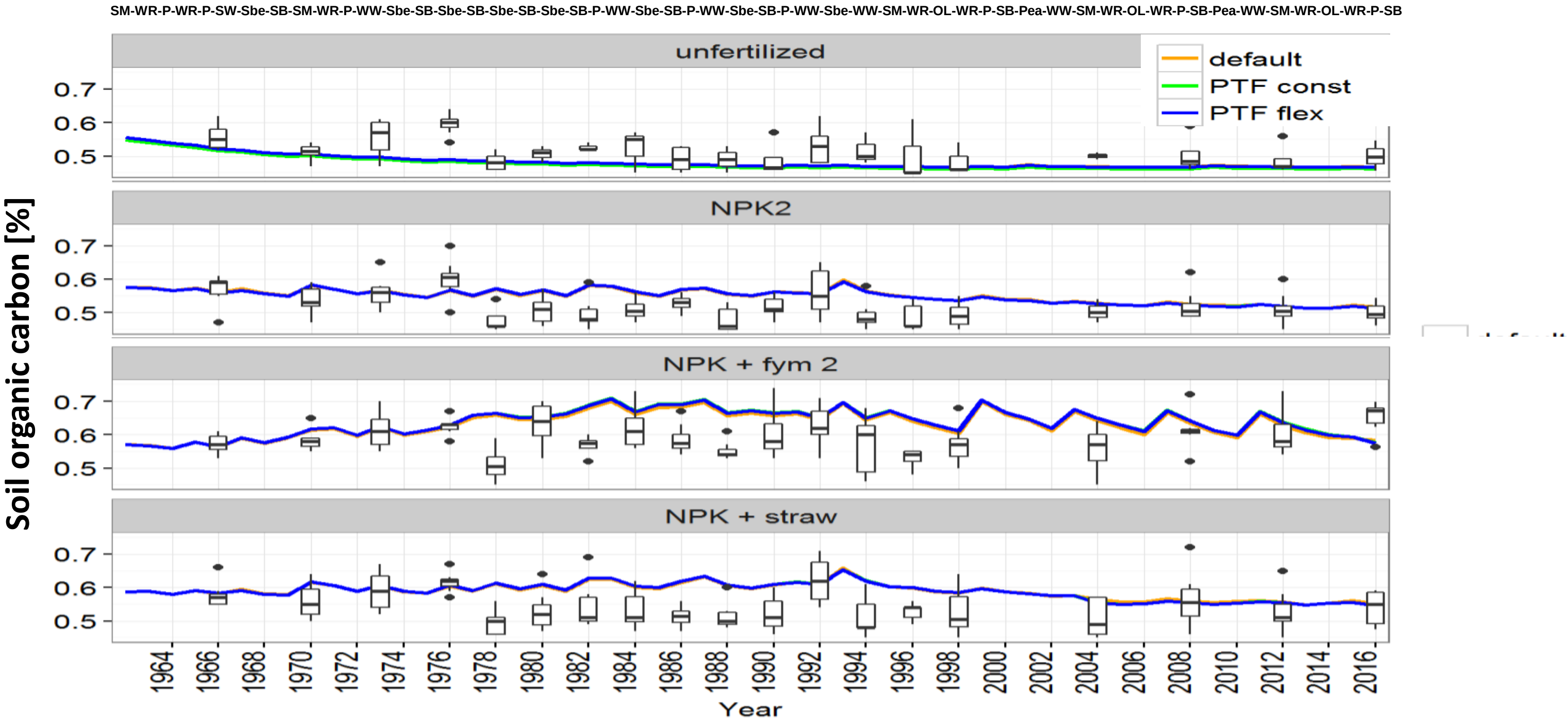
Fig. 5. Comparison of the contribution of the CO_2 transpiration effect (Eq. (7); M_H) to the combined CO_2 effect (M_H+) for two different climates (continental: precipitation <510 mm yr^{-1}, maritime: precipitation >700 mm yr^{-1}) at sites with groundwater-affected Fluvisols and with sandy and loamy soils without groundwater influence.

Kersebaum & Nendel 2014

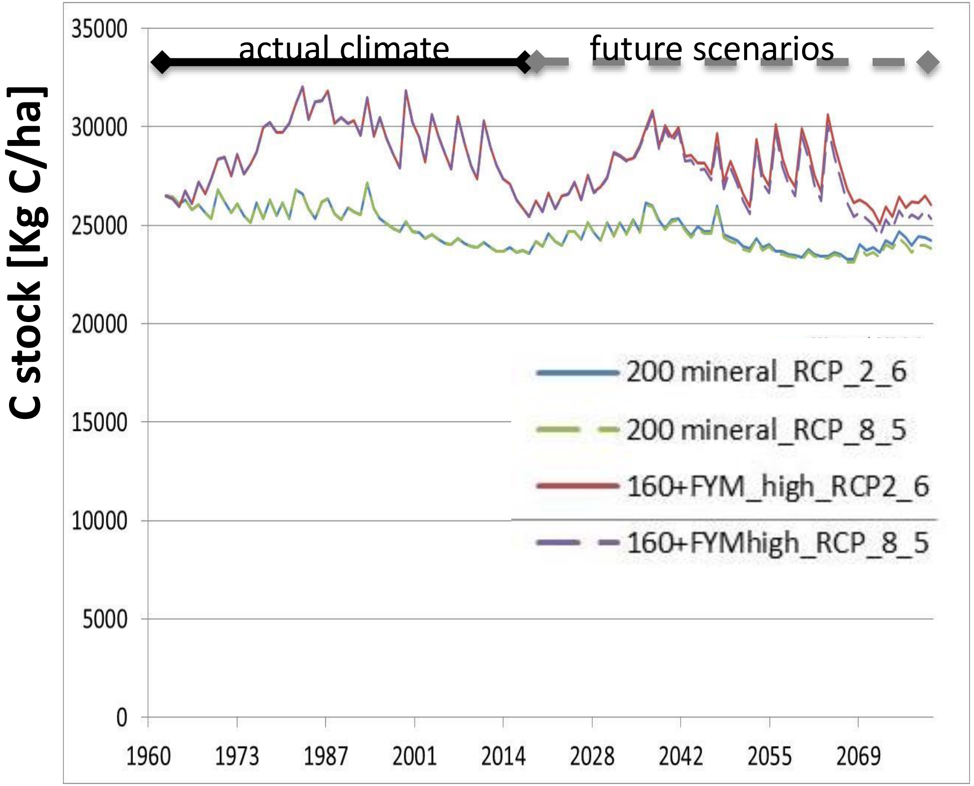
Conclusion:

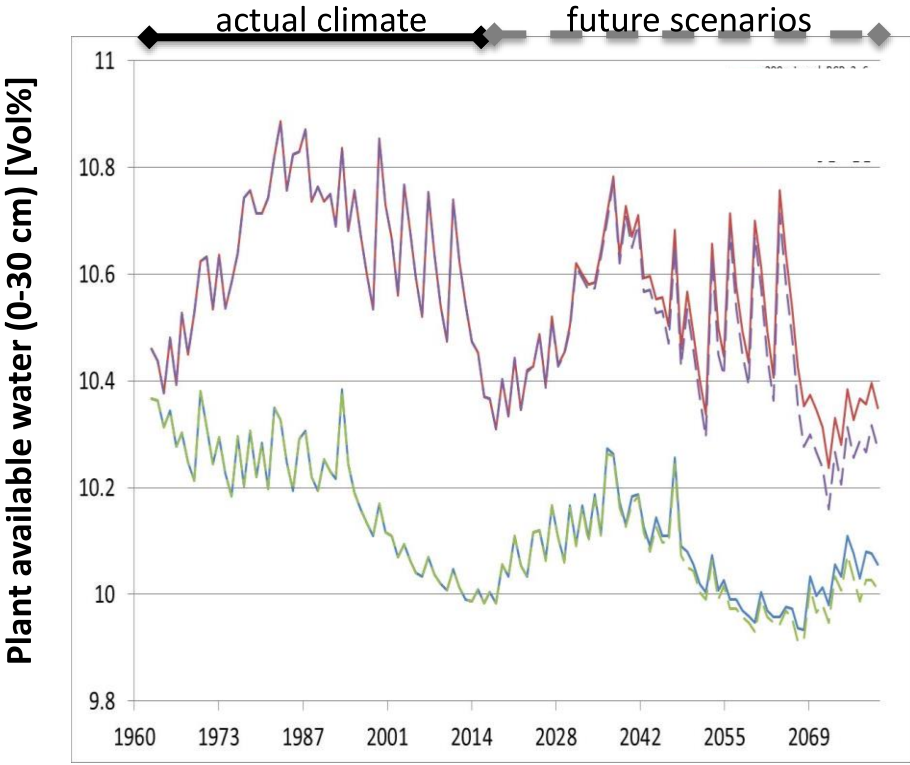
reduced stomata conductance may bridge moderate water stress, but does not compensate long severe drought

Simulated and observed effects of fertilizer treatments on soil organic carbon (0-30 cm) in Müncheberg LTFE



Comparison of simulated soil organic matter stocks (0-30 cm) and plant available water for two plots





How is C sequestration related to nitrogen and N_2O emissions?

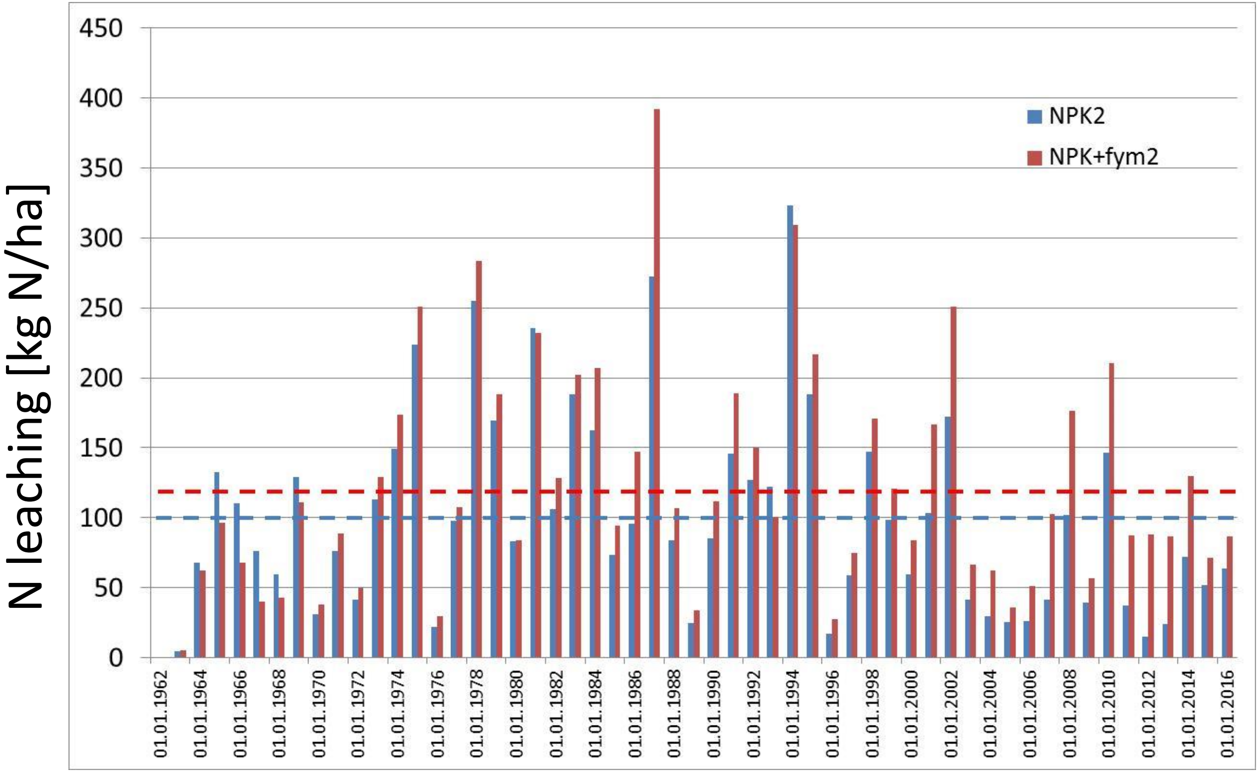
Environmental Science & Technology
Viewpoint
pubs.acs.org/est

Sequestering Soil Organic Carbon: A Nitrogen Dilemma

Jan Willem van Groenigen,[*,†] Chris van Kessel,[‡] Bruce A. Hungate,[§] Oene Oenema,[†,∥] David S. Powlson,[⊥] and Kees Jan van Groenigen[‡,#]

- **Main statements:**
- Soil organic matter (SOM) contains nitrogen (N) as well as C, and it is unclear what will be the origin of this N.
- Implementing the 4 per mile initiative on all agricultural soils would require a SOC sequestration rate of 1200 Tg C yr^{-1} .
- Assuming an average C-to-N ratio of 12 in SOM, this would require 100 Tg N yr^{-1}.
- This equals an increase of ∼75% of current global N-fertilizer production, or extra symbiotic N_2 fixation rates equaling twice the current amount in all agricultural systems.
- In theory, the current N surplus in global agroecosystems would be sufficient to provide the required 100 Tg N yr^{-1} .
- However, these surpluses are not evenly distributed but concentrated in specific regions.
- Even if the N surpluses were more evenly distributed, they would first have to be accumulated by crops in order to supply organic C to the soil.
- The rate of N accumulated in global cropland residue is estimated to be ∼30 Tg N yr^{-1}

Simulated annual N leaching for two selected plots with similar soil properties and different N treatments



Müncheberg long term field trial

Long term crop rotation effects on soil C, N and N_2O emissions

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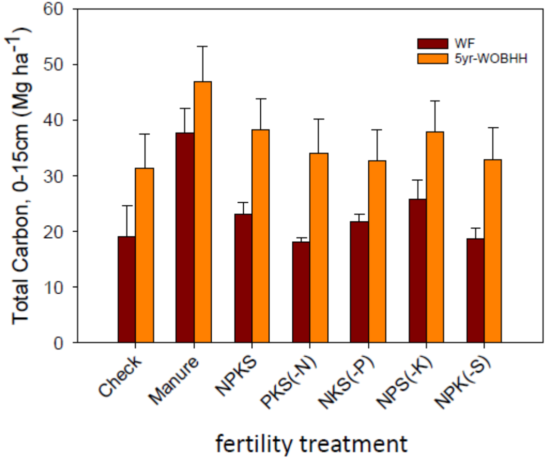
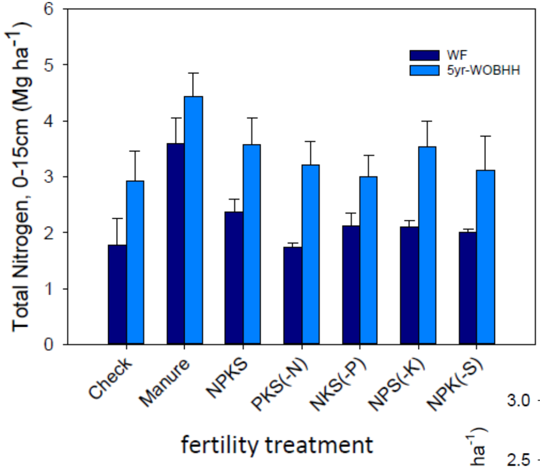
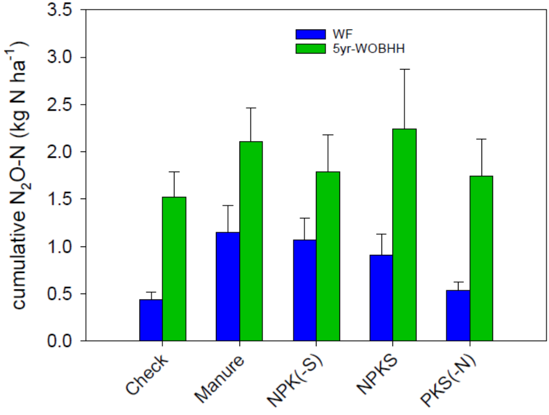
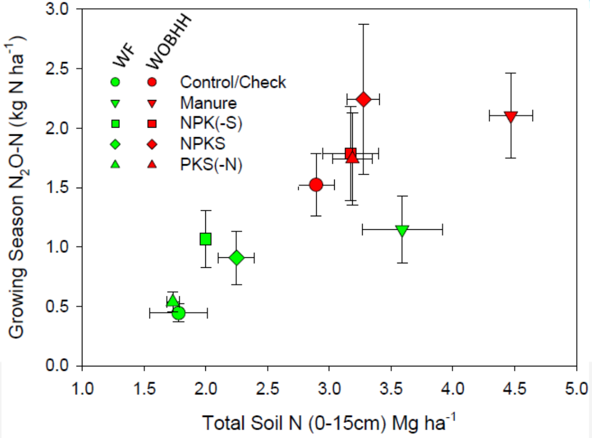
Carbon and nitrogen stocks depending on crop rotation and treatments (LTFE Breton, Canada, est. 1930)





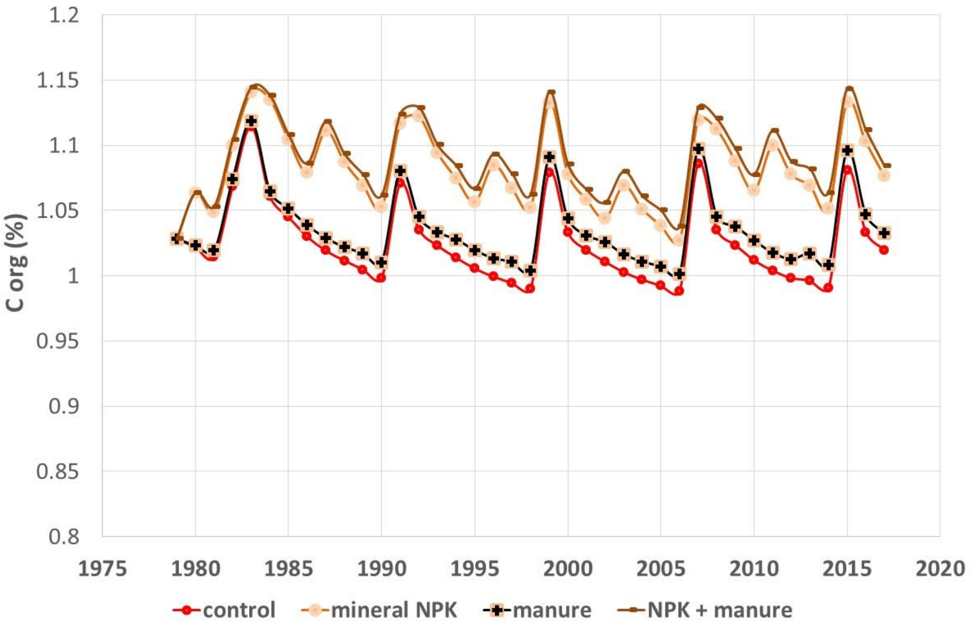
Cumulative growing season N_2O emissions (2013-2016)

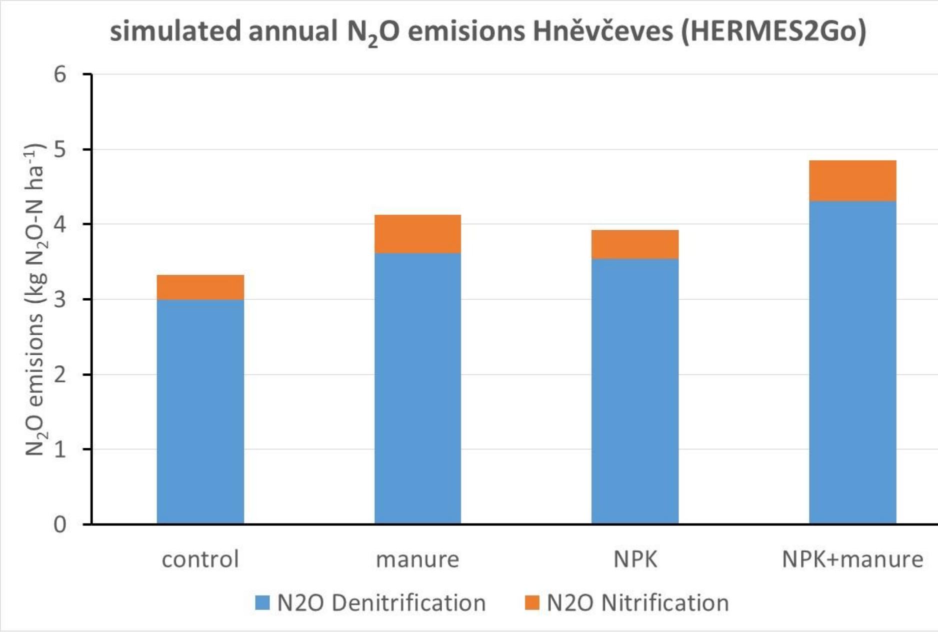




M. Dyck 2019

First results of Corg and annual sums of N_2O fluxes for a long term field experiment at Hnevceves (Cz)





Assessment of biotic stress on crop growth

- Crop models are considering water and nutrient limitations, but rarely damages from pest and diseases.
- There are models describing pest and disease development depending on weather variables.
- Interdependencies 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.
- Estimation of crop loss could improve

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

Damages caused by P&D, which can be linked to crop models

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

[a] Derived from Rabbinge and Vereyken (1980), Rabbinge and Rijsdijk (1981) and Boote et al. (1983).

from Savary & Willocquet

Damages light steeler and assimilate sapper implemented into five crop models for four fungal deseases

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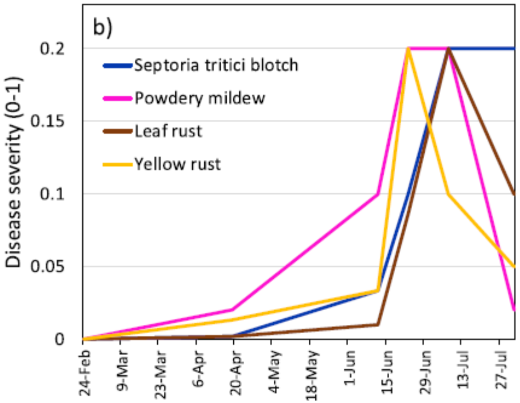
Comparing process-based wheat growth models in their simulation of yield losses caused by plant diseases

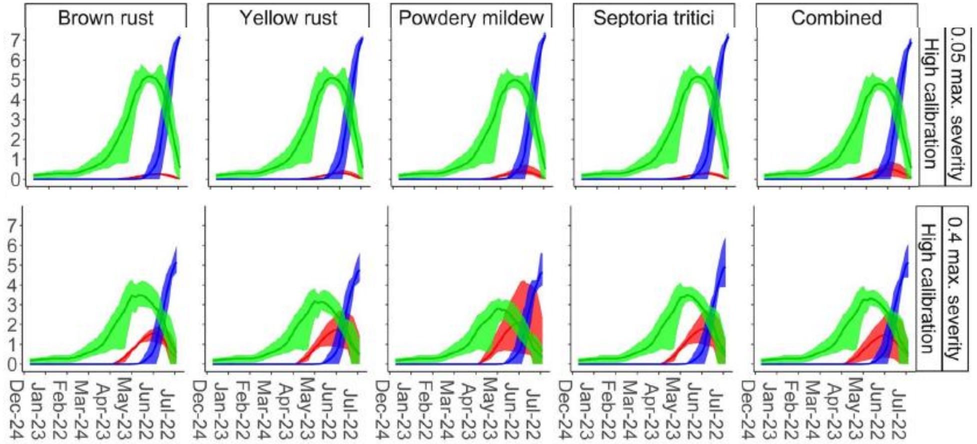
Simone Bregaglio[a,*], Laetitia Willocquet[b], Kurt Christian Kersebaum[c,g], Roberto Ferrise[d], Tommaso Stella[c], Thiago Berton Ferreira[e], Willingthon Pavan[e,h], Senthold Asseng[f,1], Serge Savary[b]

Models:
DSSAT-NWHEAT
HERMES
SSM-WHEAT
WHEATPEST
WOFOST GT

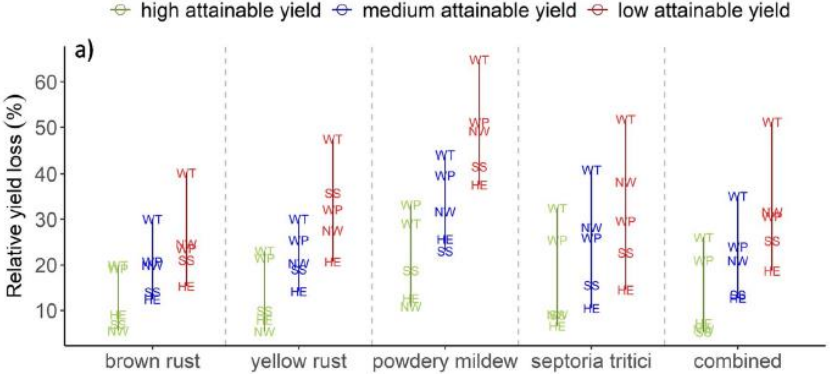
Using ideotypic severity courses of each fungal disease



Green and injured leaf area (unitless) and grain dry matter (t ha^{-1})



Yield loss (%) by single and combined desease infection



Concluding thoughts

„All models are wrong but some are useful.“

by George Box (1979)

Is the model the best way to answer the question?

→ **There is no best way and there is no unique model!**

But in many cases a model is a better way to understand a real system than any other known approach.

→ **Find an appropriate (a useful) model!**

Thank you for your attention