

# Yield gap decomposition to identify constraints to crop production in farmers' fields



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# Introduction

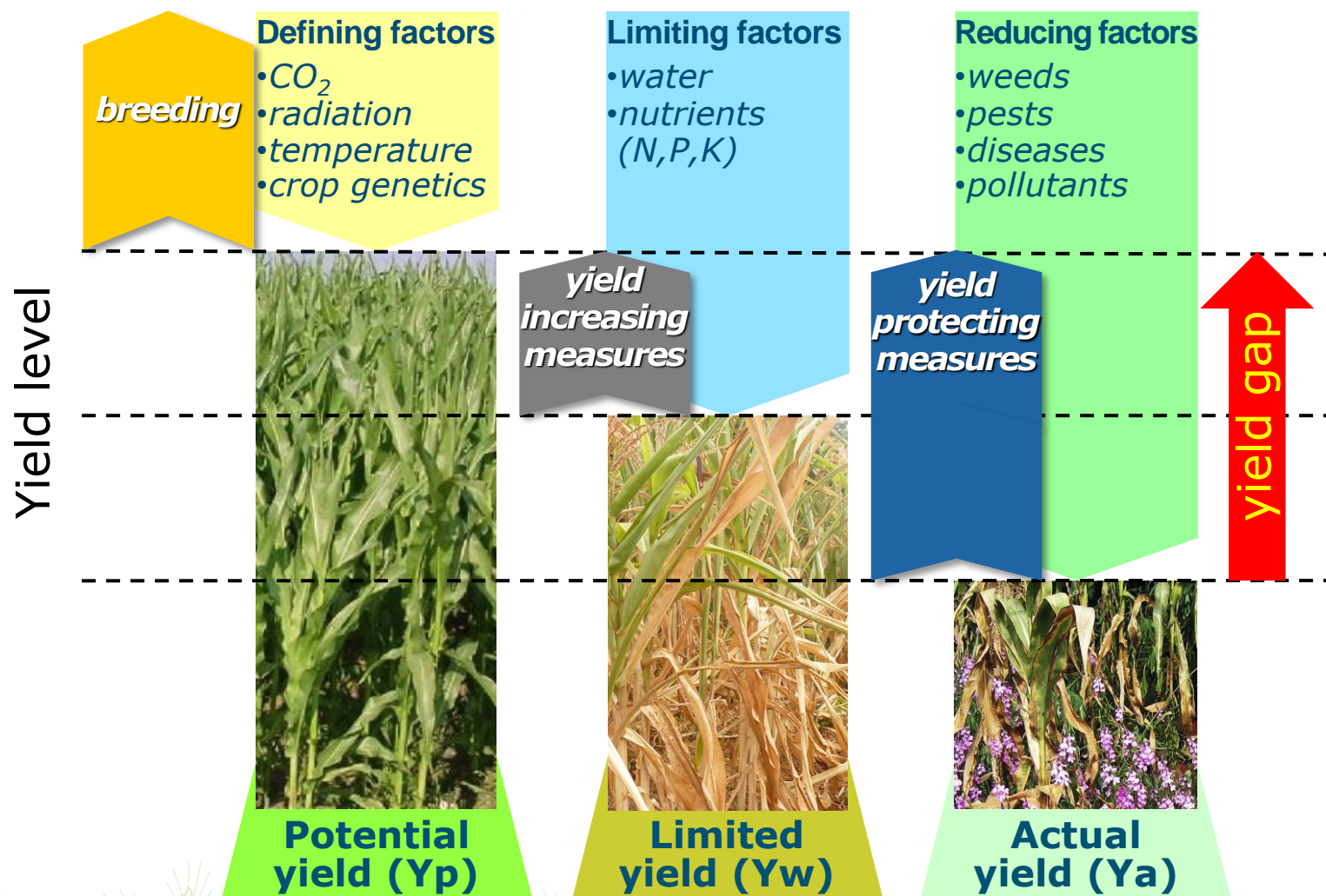
1. Yield gaps to inform food security assessments and delineate scope for sustainable intensification.
2. Understand the relative contribution of growth defining, limiting, and reducing factors to actual farm yields.
3. Increasing availability of farmer field data, and environmental data, both across space and over time.
4. Prioritization of R&D based on the most limiting factors to crop production.

**Objective:** Overview of modelling and data-driven and approaches\*\* for yield gap decomposition using farmer field data.

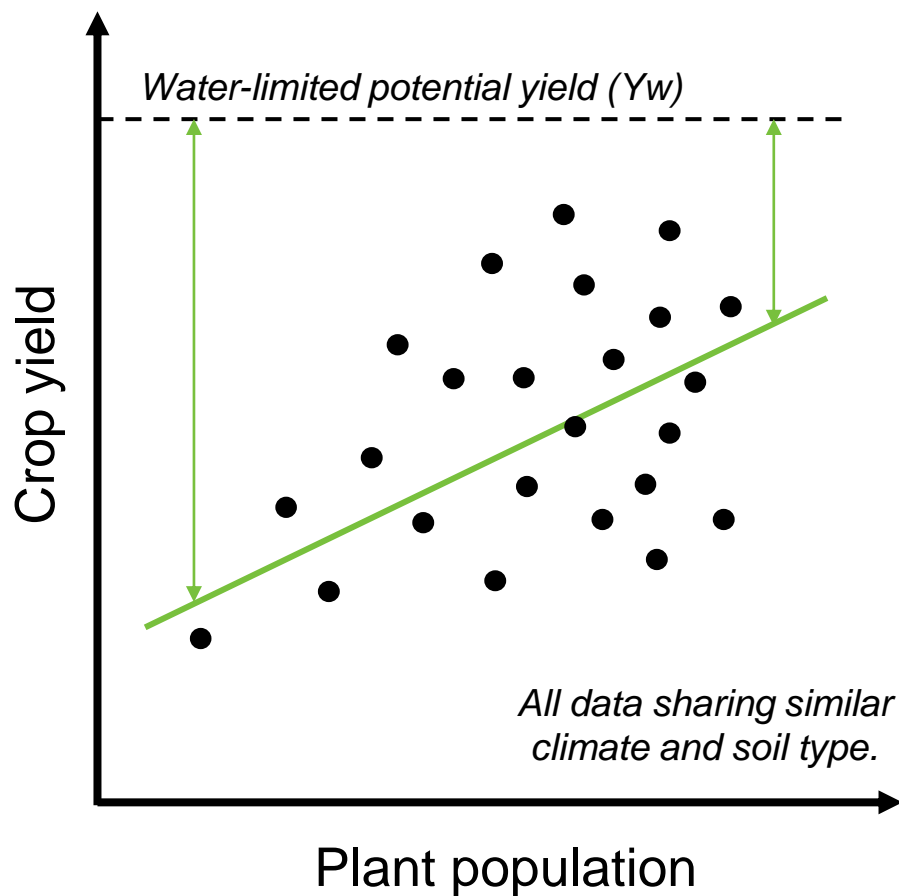
*\*\*Expert-based or experimental assessments not covered.*



# Concepts of production ecology



# What is yield gap decomposition?

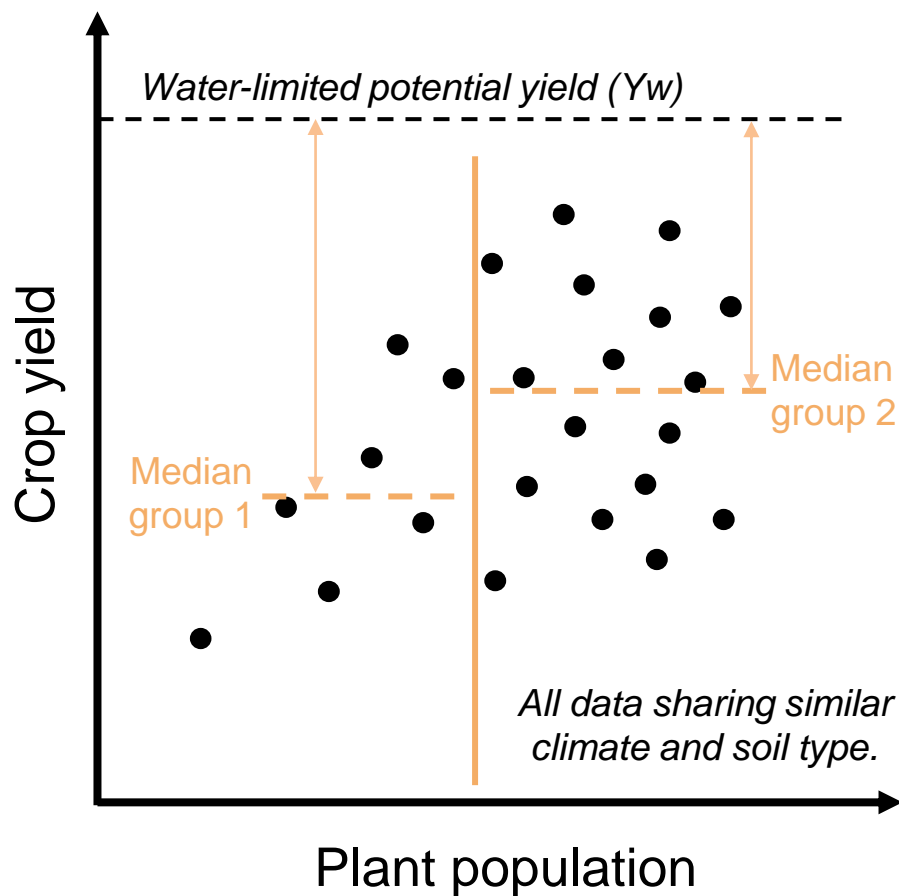


**Regression approach:**  $y = ax + b + \varepsilon$   
Crop yield increases with plant population, on average. Slope indicates rate of change.





# What is yield gap decomposition?

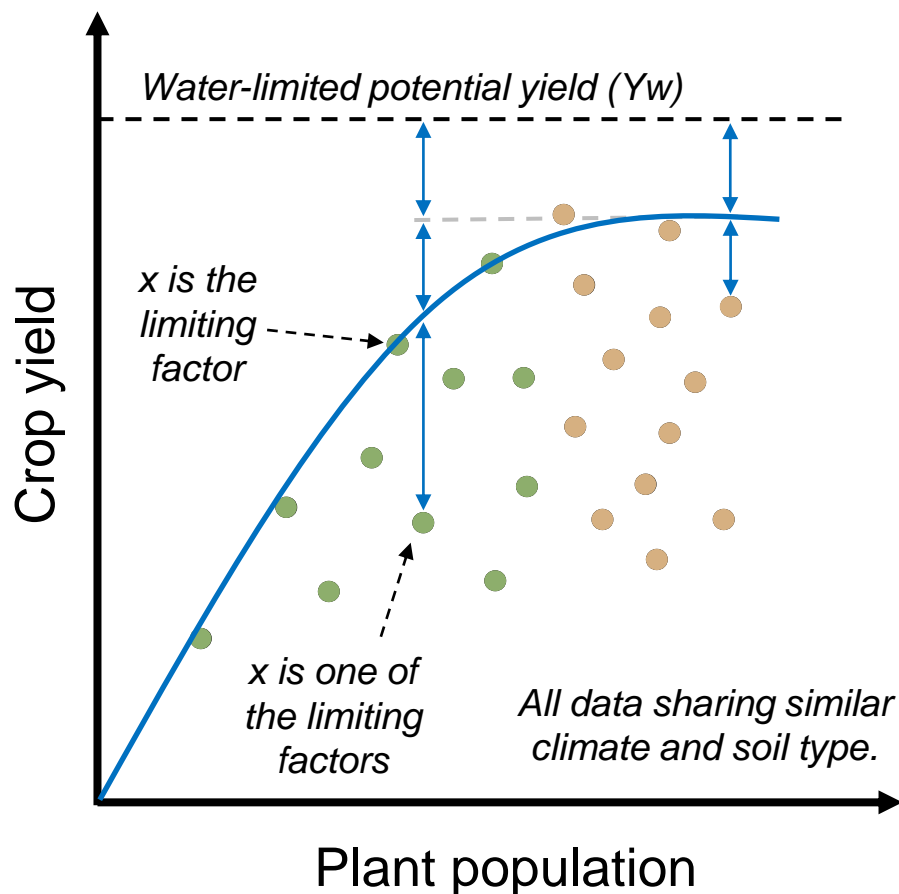


**Regression approach:**  $y = ax + b + \varepsilon$   
Crop yield increases with plant population, on average. Slope indicates rate of change.

**Tree-based approach:** *non-parametric*  
Data space partitioned into a group with low plant population and low yield, and a group with high plant population and high yield.



# What is yield gap decomposition?



**Regression approach:**  $y = ax + b + \varepsilon$   
Crop yield increases with plant population, on average. Slope indicates rate of change.

**Tree-based approach:** *non-parametric*  
Data space partitioned into a group with low plant population and low yield, and a group with high plant population and high yield.

**Frontier approach:**  
In half the observations the yield gap is due to plant population. In the other half, the yield gap is explained by factors other than plant population.

**Yield gap analysis is related to analysis of actual yield variability, but it is not the same!**



# Process-based crop models

## Simulation of yield levels



### Catching-up with genetic progress: Simulation of potential production for modern wheat cultivars in the Netherlands

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**Keywords:**  
 LINTUL3  
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 Light use efficiency  
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 Potential yield  
 Winter wheat  
 Phenology

#### ABSTRACT

**Context:** Wheat crop growth models from all over the world have been calibrated on the Groot and Verbeke (1991) data set, collected between 1962 and 1984 in the Netherlands, in at least 20 published studies to date including various recent ones. However, the recent use of this data set for calibration of potential yield is questionable as actual Dutch winter wheat yields increased by 3.1 Mg ha<sup>-1</sup> over the period 1984–2015. A new comprehensive set of winter wheat experiments, suitable for crop model calibration, was conducted in Wageningen during the growing seasons of 2013–2014 and of 2014–2015.

**Objective:** The present study aimed to quantify the change of winter wheat variety traits between 1984 and 2015 and to examine which of the identified traits explained the increase in wheat yield.

**Methods:** PCER-LINTUL3 was calibrated on the Groot and Verbeke data (1991) set. Next, it was evaluated on the 2013–2015 data set. The model was further recalibrated on the 2013–2015 data set. Parameter values of both calibrations were compared. Sensitivity analysis was used to assess to what extent climatic change, elevated CO<sub>2</sub>, changes in sowing dates, and changes in cultivar traits could explain yield increases.

**Results:** The estimated reference light use efficiency and the temperature sum from anthesis to maturity were higher in 2013–2015 data in 1962–1984. PCER-LINTUL3, calibrated on the 1962–1984 data set, underestimated the yield potential of 2013–2015. Sensitivity analyses showed that about half of the simulated winter wheat yield increase between 1984 and 2015 in the Netherlands was explained by elevated CO<sub>2</sub> and climate change. The remaining part was explained by the increased temperature sum from anthesis to maturity and, to a smaller extent, by changes in the reference light use efficiency. Changes in sowing dates, biomass partitioning fractions, thermal requirements for anthesis, and biomass reallocation did not explain the yield increase.

**Conclusions:** Recalibration of PCER-LINTUL3 was necessary to reproduce the high wheat yields currently obtained in the Netherlands. About half of the reported winter wheat yield increase was attributed to climate change and elevated CO<sub>2</sub>. The remaining part of the increase was attributed to changes in the temperature sum from anthesis to maturity and, to a lesser extent, the reference light use efficiency.

**Significance:** This study systematically addressed to what extent changes in various cultivar traits, climate change, and elevated CO<sub>2</sub> can explain the winter wheat yield increase observed in the Netherlands between 1984 and 2015.

#### 1. Introduction

Crop growth and yield are the result of interactions between crop genetic factors, environmental conditions, and crop management (often referred to as G × E × M; Hatfield and Wallach, 2019). Crop growth models simulate the development and growth of crops in a dynamic way

and thereby take these factors, and their interactions, into account (Boote et al., 1996; Wallach et al., 2019). This makes crop modelling a useful tool for a wide range of applications (van Ieperum et al., 2003) including yield-gap analysis (Schulze et al., 2010), optimisation of crop management practices (McNair et al., 2019), yield forecasting (Pavelle et al., 2021), decision-support (Pykalidis et al., 2021; Divya et al.,

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## Simulation of mgt practices



### Revisiting yield gaps and the scope for sustainable intensification for irrigated lowland rice in Southeast Asia

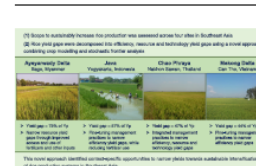
João Vasco Silva<sup>a,b,\*</sup>, Valerian O. Pede<sup>c</sup>, Ando M. Radanielson<sup>a,c</sup>, Wataru Kodama<sup>d</sup>, Ary Duarte<sup>a,c</sup>, Annalyn H. de Guia<sup>e</sup>, Arelene Julia B. Malabayabas<sup>f</sup>, Arlyna Budi Puritika<sup>g</sup>, Nuning Argosubekti<sup>h</sup>, Duangporn Vithoonjit<sup>i</sup>, Pham Thi Minh Hieu<sup>b</sup>, Amny Ruth P. Pame<sup>j</sup>, Grant R. Singleton<sup>a</sup>, Alexander M. Stuart<sup>a</sup>

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#### HIGHLIGHTS

- Analysis rice yield gaps is needed to better understand how to sustainably increase rice production across Southeast Asia.
- Rice yield gaps (Yg) for four countries in Southeast Asia were decomposed into efficiency, resource, and technology Yg.
- Ygs were mainly attributed to resource and technology Yg in Myanmar, and to efficiency and technology Yg in Indonesia.
- Yg closure requires increased N in Myanmar, reduced N in Indonesia, and fine-tuning N management in Thailand and Vietnam.
- This novel approach identified opportunities for sustainable intensification of rice production in Southeast Asia.

#### GRAPHICAL ABSTRACT



#### ARTICLE INFO

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**Keywords:**  
 Crop modeling  
 Stochastic frontier analysis

#### ABSTRACT

**CONTEXT:** Recent studies on yield gap analysis for rice in Southeast Asia revealed different levels of intensification across the main 'rice bowls' in the region. Identifying the key crop management and biophysical drivers of rice yield gaps across different 'rice bowls' provides opportunities for compensatory analyses, which are crucial to better understand the scope to narrow yield gaps and increase resource-use efficiencies across the region.

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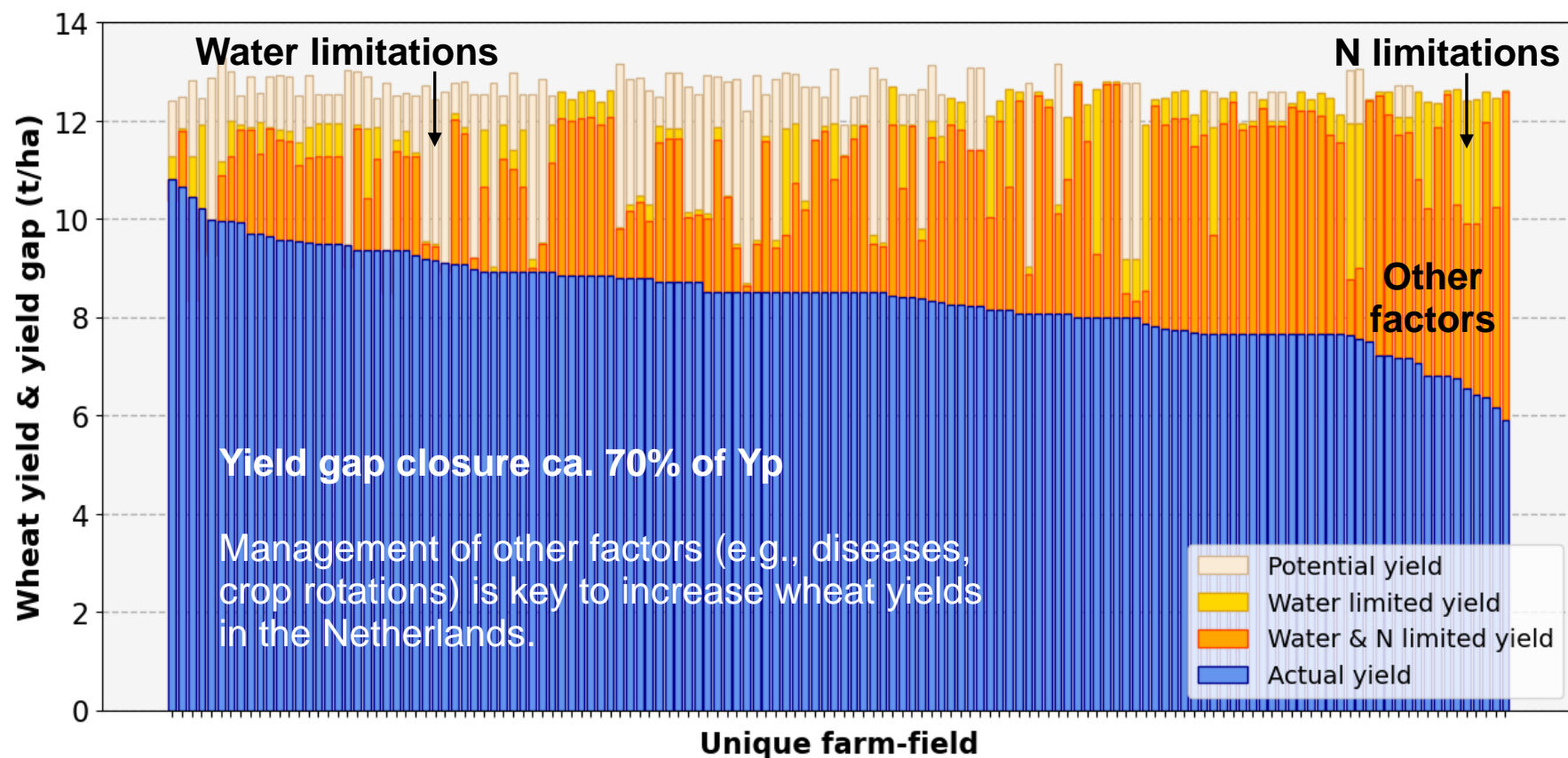
# Simulation of yield levels

## ❖ Winter wheat crops in the Netherlands:

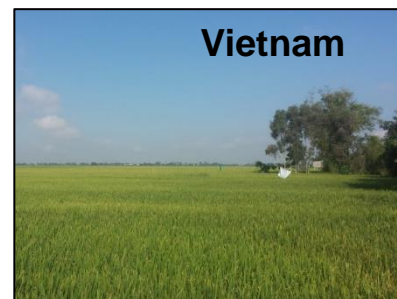
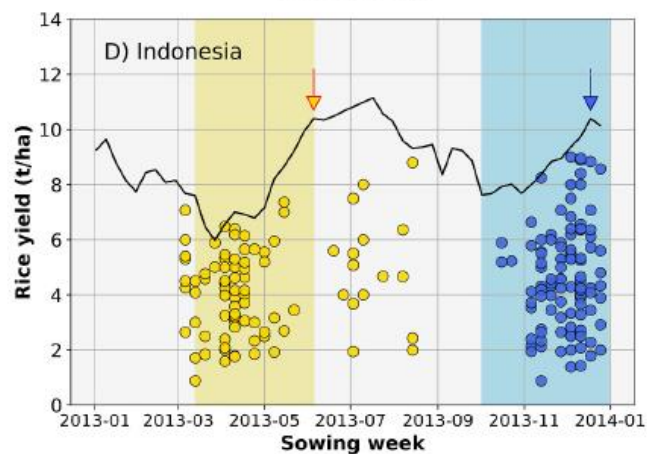
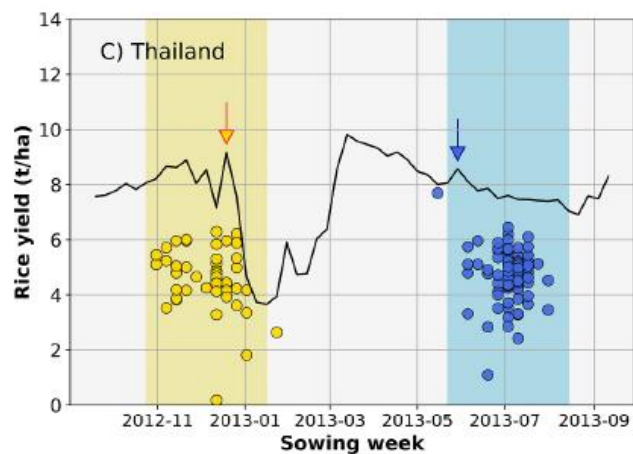
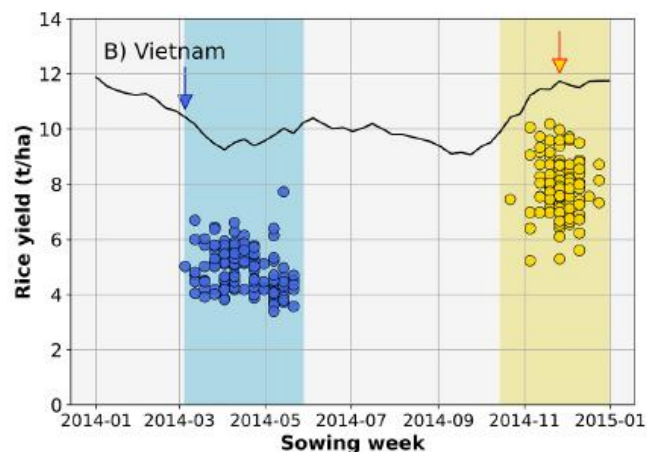
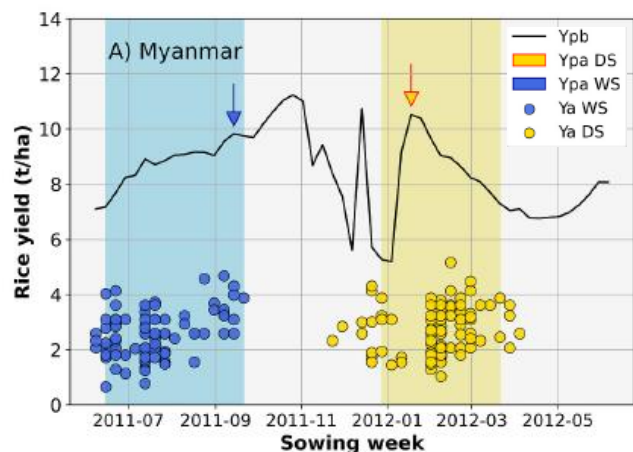
- ❖ High-yielding crop, due to high input use and intensive management
- ❖ Important in the rotation to ensure high-yields of tuber/root crops



# Simulation of yield levels



# Simulation of mnngt practices



Silva et al. (2022, AgSys)



# Data-driven approaches

## Boundary lines (Fermont et al., 2009)



### Closing the cassava yield gap: An analysis from smallholder farms in East Africa

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Cassava

Production constraints

Soil fertility

Yield management

#### ABSTRACT

Cassava yields in Africa are small and it remains unclear what factors most limit yields. Using a series of farm surveys and on-farm and on-station trials in Uganda and western Kenya, we evaluated the importance of abiotic, biotic and associated crop management constraints for cassava production in a range of socio-economic settings as found in smallholder farms in the region. Average yields under farmer management were 8.6 t ha<sup>-1</sup>, but these were more than doubled to 20.8 t ha<sup>-1</sup> by using improved crop establishment, improved genotypes and 100–220 kg ha<sup>-1</sup> of single-nutrient N–P–K fertilizers. A farm survey revealed large yield differences between farms. Less-endowed farmers harvested less cassava per unit area than better-endowed farmers (difference of 5 and 9.7 t ha<sup>-1</sup> in Kenya and Uganda, respectively); differences were associated with less access to labour, poorer soils, and less pressure harvesting by less-endowed farmers. Analysis of 99 on-farm and 6 on-station trials showed that constraints for cassava production varied strongly between farms and years. Poor soil fertility, early water stress and sub-optimal weed management limited cassava production by 6.7, 5.4 and 5.0 t ha<sup>-1</sup>, respectively, when improved crop establishment and genotypes were used. Pests and diseases were relatively unimportant, while weed management was particularly important in farmer fields during a dry year in Kenya (44% gap of 11.6 t ha<sup>-1</sup>). The use of complementary analytical tools such as multiple regression and boundary line analysis revealed that many fields were affected by multiple and interacting production constraints. These should be addressed simultaneously to significantly improve productivity and to be achieved. This will be most difficult for less-endowed farms but better-endowed farm households, since the former lack social and financial capital to improve management.

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#### 1. Introduction

Cassava research and extension efforts in Africa have successfully focused on breeding and integrated pest management (IPM) strategies to control major pests and diseases, most notably mosaic virus, mealy bugs and green stink bugs (Asten et al., 2006; Legg et al., 2006; Zano et al., 2007). While the major focus of such efforts was placed on coping with biotic constraints, relatively little attention has been given to abiotic, crop management and socio-economic constraints. Understanding the relative importance of these factors to the yield gap is a necessary step to guide the design of relevant research for development interventions aimed at improving cassava productivity. This has been acknowledged by scientists who recently initiated a worldwide exercise to gather expert knowledge on the contribution of various constraints to the

cassava yield gap in the main agro-ecological regions where cassava is grown (Generation Challenge Programme, 2008, p. 82). The yield gap is generally defined as the difference between actual farmer yields and potential yield, whereby potential yield is the maximum yield that can be achieved in a given agro-ecological zone. For practical purposes it is, however, more interesting to study the gap between the actual and attainable yield, whereby the attainable yield can be defined as the maximum yield observed in a given agro-ecological zone with a given management intensity.

The mid-altitude zones of East Africa constitute a major cassava growing region in Africa and cover a wide range of agro-ecological conditions. Some of these are well represented in areas of Kenya and Uganda. Average fresh yields at country level in 2007 were 10.1 t ha<sup>-1</sup> in Kenya and 12.0 t ha<sup>-1</sup> in Uganda, which was just above the African average of 9.9 t ha<sup>-1</sup> (FAO, 2008), but far below typical average fresh yields of 15–40 t ha<sup>-1</sup> obtained in on-farm breeding trials in these countries (Nawarungu et al., 2006; Fermont et al., 2007). According to Cock et al. (1979) the ideal cassava plant, consisting of a late branching genotype that possesses large leaves with a long leaf life, would have a potential yield of 25–30 t ha<sup>-1</sup> dry roots, equivalent to fresh roots yields in

## Stochastic frontiers (Silva et al., 2017)



### Explaining rice yields and yield gaps in Central Luzon, Philippines: An application of stochastic frontier analysis and crop modelling

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Crop modelling

#### ABSTRACT

Explaining yield gaps is crucial to understand the main technical constraints faced by farmers to increase land productivity. The objective of this study is to decompose the yield gap into efficiency, resource and technology yield gaps for irrigated lowland rice-based farming systems in Central Luzon, Philippines, and to explain these yield gaps using data related to crop management, biophysical constraints and available technologies. Stochastic frontier analysis was used to quantify and explain the efficiency and resource yield gaps and a crop growth model (ORYZA v3) was used to compute the technology yield gap. We combined these two methodologies into a theoretical framework to explain rice yield gaps in farmers' fields isolated in the Central Luzon Long Survey, an unbalanced panel dataset of about 100 households, collected every five years from the period 1962–2012. The mean yield gap estimated for the period 1979–2012 was 3.2 t ha<sup>-1</sup> in the wet season (WS) and 4.8 t ha<sup>-1</sup> in the dry season (DS). An average efficiency yield gap of 1.3 t ha<sup>-1</sup> was estimated and partly explained by untimely application of mineral fertilizers and biotic control factors. The mean resource yield gap was small in both seasons but somewhat larger in the DS (1.3 t ha<sup>-1</sup>) than in the WS (1.0 t ha<sup>-1</sup>). This can be partly explained by the greater N–P and K use in the highest yielding fields than in lower yielding fields which was observed in the DS but not in the WS. The technology yield gap was on average less than 1.0 t ha<sup>-1</sup> during the WS prior to 2003 and as 1.6 t ha<sup>-1</sup> from 2003 to 2012, while in the DS it has been consistently large with a mean of 2.2 t ha<sup>-1</sup>. Varietal shift and sub-optimal application of inputs (e.g. quantity of irrigation water and N) are the most plausible explanations for this yield gap during the WS and DS, respectively. We conclude that the technology yield gap explains nearly half of the difference between potential and actual yields while the efficiency and resource yield gaps explain each a quarter of that difference in the DS. As for the WS, particular attention should be given to the efficiency yield gap which, although decreasing with time, still accounted for nearly 40% of the overall yield gap.

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#### 1. Introduction

Agronomists and agricultural economists have developed different concepts and quantitative methods to estimate and explain yield gaps, i.e. the difference between climatic potential and actual farmers' yields. Agronomic studies traditionally rely on field experiments (e.g. Abalos et al., 2012) and/or crop growth models (e.g. Araghi et al., 2012) to assess the contribution of different management practices to crop yield following the so-called

theory of production ecology (van Ittersum and Rabbinge, 1997). The main limitation of these types of studies is that these do not explicitly take into account farmers' objectives and constraints (and other socio-economic conditions) because they are usually performed at field and regional levels (Dara et al., 2010). On the other hand, production economics deals with the estimation and interpretation of technical and allocative efficiencies using farm level data. Technical efficiency can be defined as the maximum output that can be achieved given a specific level of inputs while allocative efficiency refers to the success of a farm in choosing the optimal proportion of inputs given a pre-defined objective and set of constraints (Farnili, 1957). Although this methodology is highly flexible and versatile (Tham et al., 2001; Bravo-Luna and Pimonte, 1995), its outcomes are heavily dependent on the inputs used and

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## Machine learning (Nayak et al., 2022)



### Interpretable machine learning methods to explain on-farm yield variability of high productivity wheat in Northwest India

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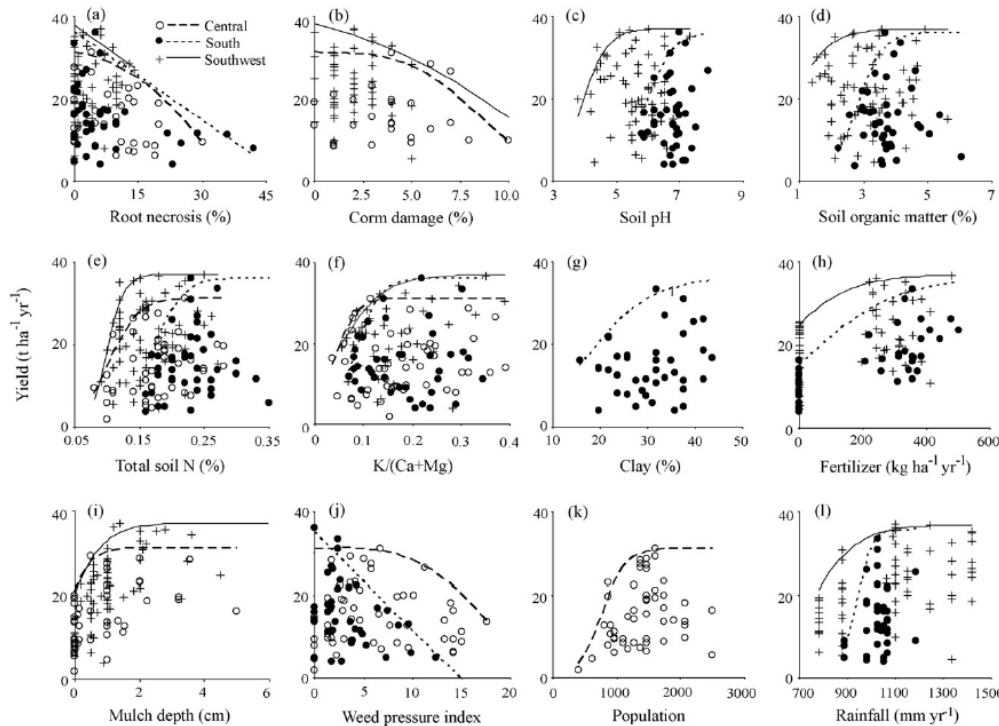
<sup>cn</sup>Indian Institute of Wheat and Maize Research, Ludhiana, India

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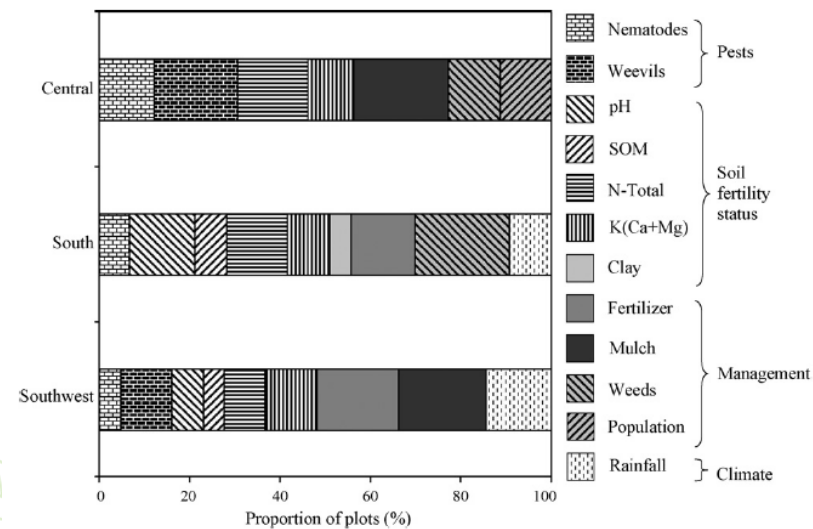
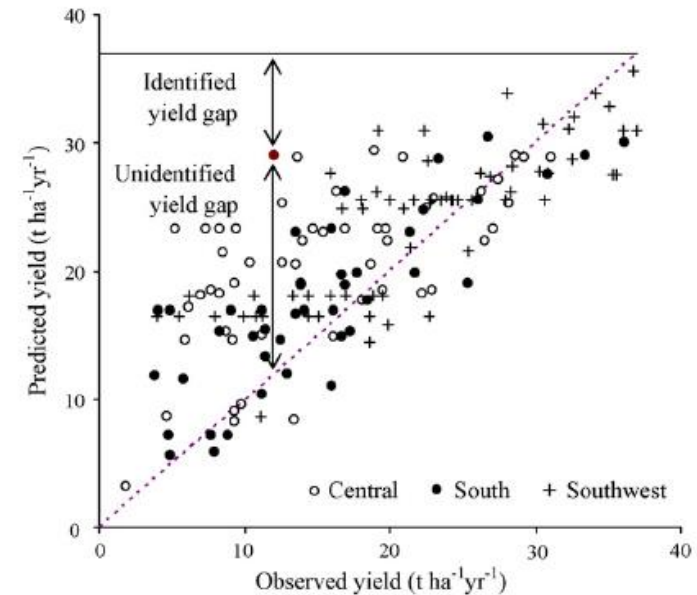
# Boundary line analysis

**Step 1:** Identify boundary line points.

**Step 2:** Estimate boundary line functions.

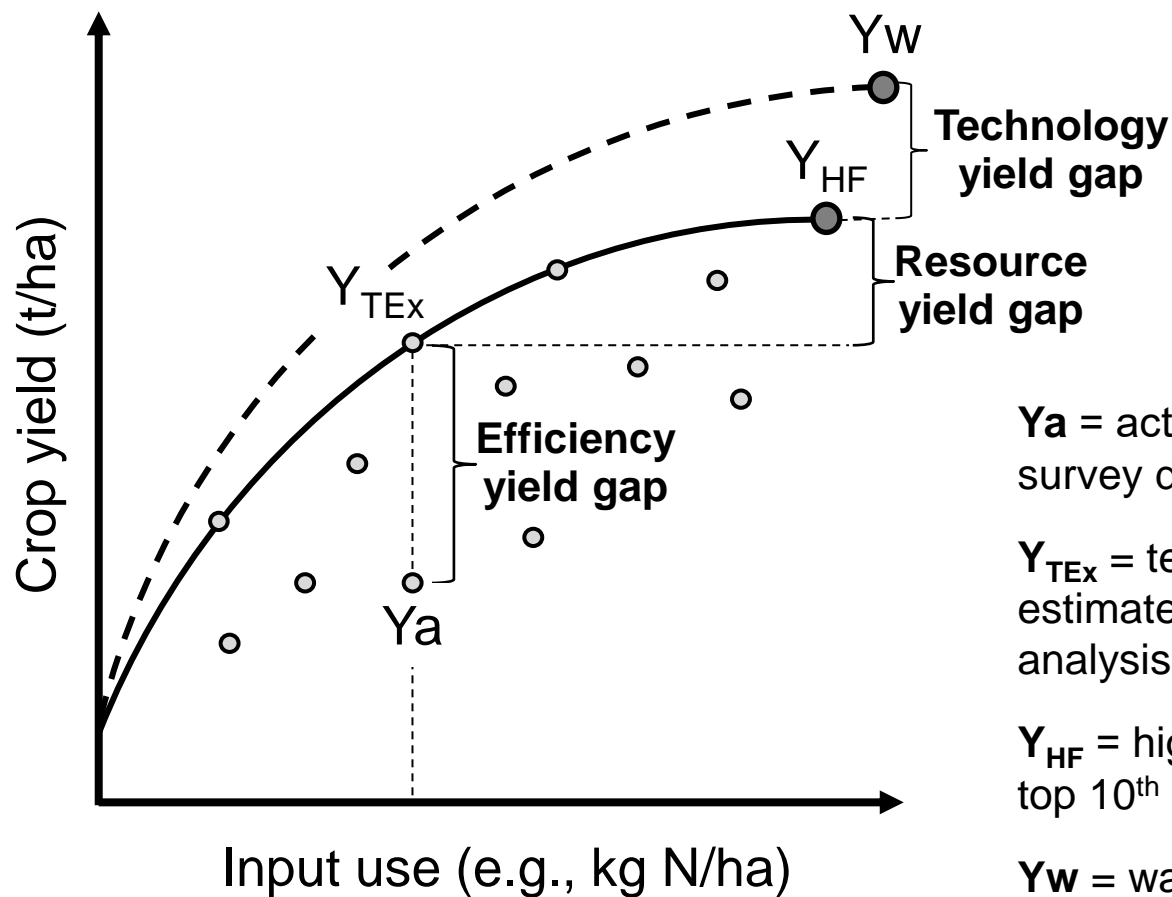


**Step 3:** Yield gap analysis and identification of limiting factors.





# Stochastic frontier analysis



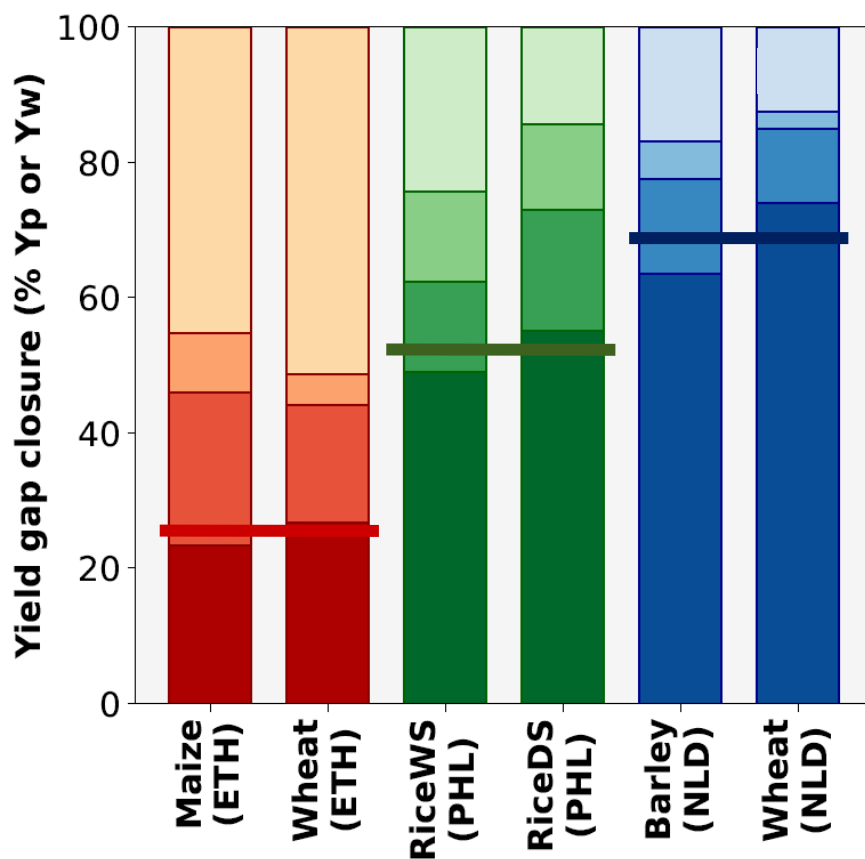
$Y_a$  = actual farmers' yields from farm survey data

$Y_{TEEx}$  = technical efficient yields estimated with stochastic frontier analysis

$Y_{HF}$  = highest farmers' yields based on top 10<sup>th</sup> percentile of  $Y_a$

$Y_w$  = water-limited potential yield from crop models

# Stochastic frontier analysis



## Southern Ethiopia

Large yield gap attributed to technology yield gaps.

Silva et al. (AgSys, 2019)

## Central Luzon, Philippines

Medium yield gap due to efficiency, resource and technology yield gaps.

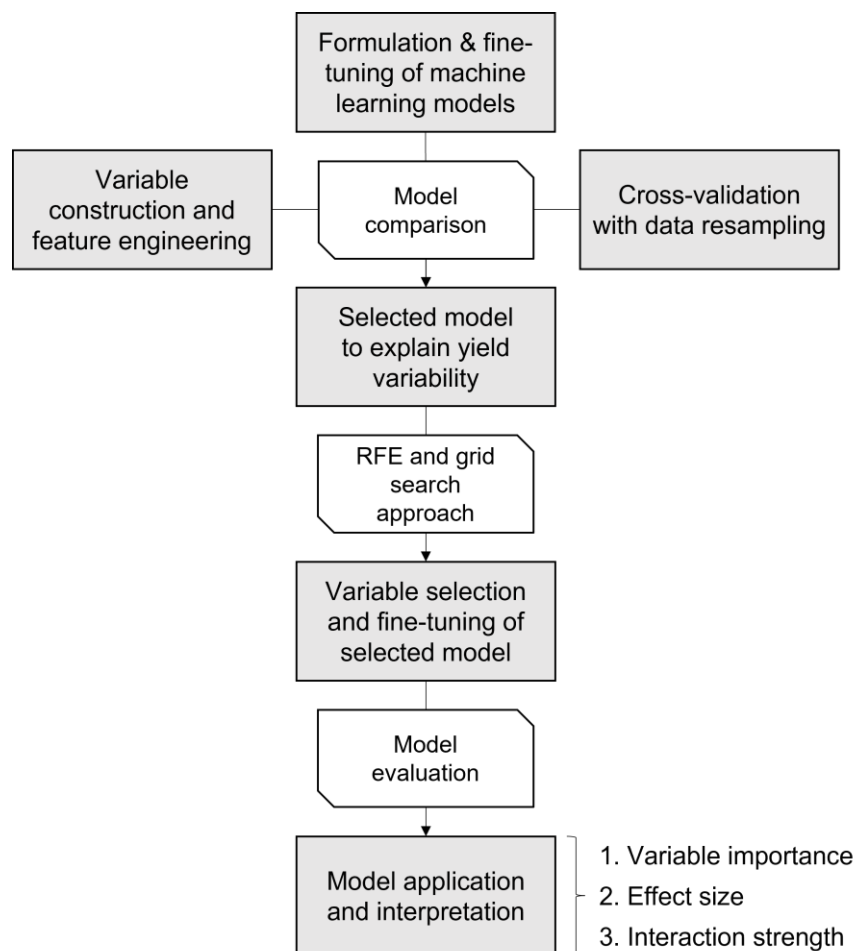
Silva et al. (2017a, EJA)

## The Netherlands

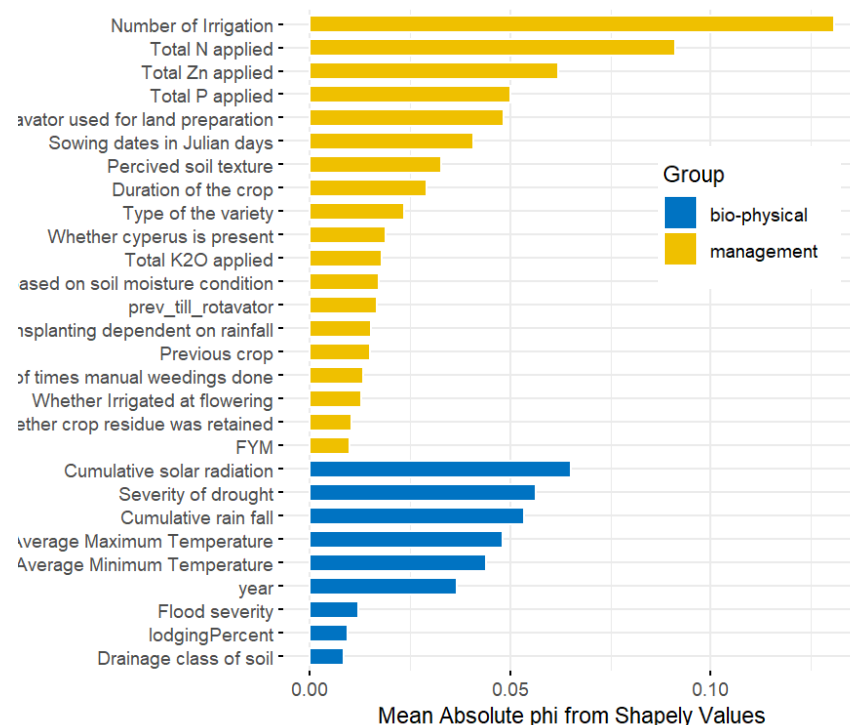
Small yield gap attributed to efficiency yield gaps.

Silva et al. (2017b, AgSys)

# Machine learning

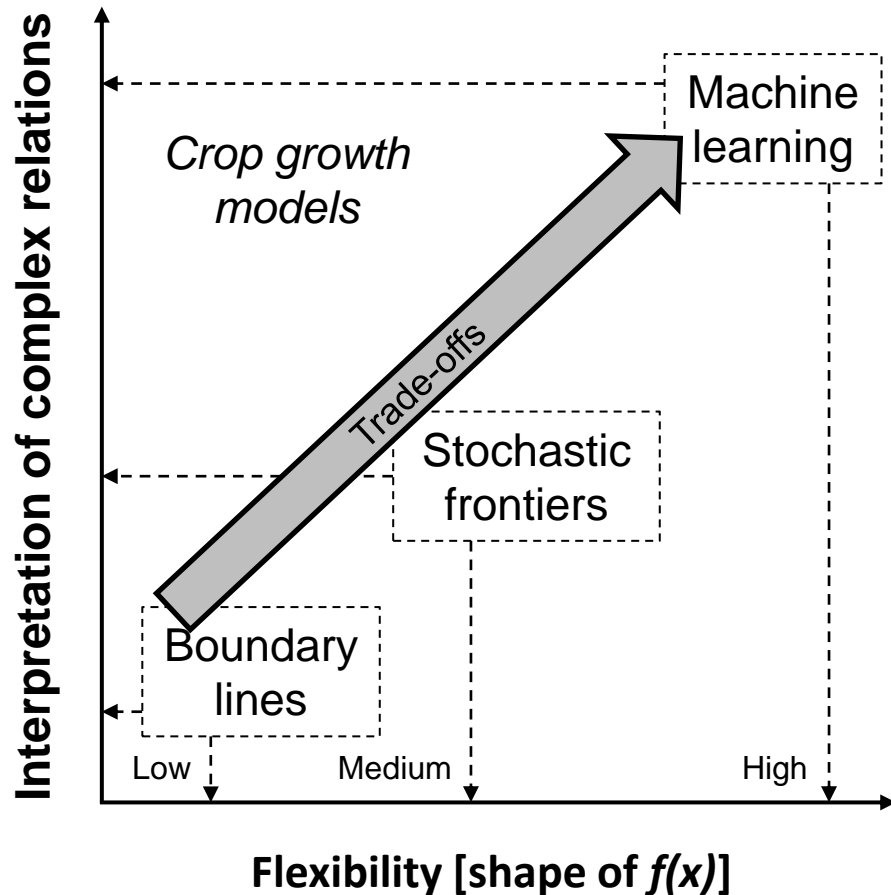


## Variable importance/Shapely values



*(!) Machine learning mostly used for analysis of actual yield variability. Its application for Yg decomposition is being finalized.*

# Summary



## Some advantages:

- All types of variables can be used
- Less sensitive to outliers
- Less subjective user decisions
- Non-linear relations and interactions accounted for
- No assumptions on functional forms
- No problem with auto-correlation

## Some disadvantages:

- High sample size
- High computation power
- No interpretability of parameters
- Script-based, Excel won't work 😊



# Strategic (future) applications

## Web-based 'one stop shop' for yield gap decomposition:

1. Interactive display on constraints to crop productivity in EiA use cases.
  2. Measurement and evaluation of agronomic gains (KPIs).
  3. Global FAIR database of on-farm yield and management practices.
  4. Achieve training materials, data collection tools, publications, etc.
  5. Connect and capacitate agronomists and data scientists.
- **Prioritization** of investments and R&D efforts to increase crop productivity in the Global South.
  - Inform national and regional **policies** dealing with food security, resource use efficiency, and environmental sustainability.







**Thank you  
for your  
interest!**